

The January 17, 1994, Northridge Earthquake, California

by

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ABSTRACT

The magnitude 6.8 earthquake occurred during the pre-dawn hours of January 17, 1994 provided a crucial test for assessing our progress in earthquake resistant design and construction over the past two decades, following a similar magnitude event, the San Fernando earthquake in 1971.

A reconnaissance team was organized by NIST through the auspices of the National Earthquake Hazards Reduction Program and the Interagency Committee on Seismic Safety in Construction, to observe the damage, assess the performance of various types of engineering structures, and document the effects of the earthquake on the built environment: buildings, bridges, and lifeline systems. This paper summarizes what we learned from the reconnaissance effort. More detailed documentation has been presented in an NIST Special Publication, 862, "1994 Northridge Earthquake: Performance of Structures, Lifelines, and Fire Protection Systems."

1. INTRODUCTION

A strong earthquake of magnitude 6.8 centered under the community of Northridge in the San Fernando Valley in California shook the entire Los Angeles area at 4:31 a.m. local time on Monday, January 17, 1994. January 17 was a federal holiday honoring Dr. Martin Luther King's birthday and, because of this and also the early morning hour, most non-residential buildings were empty and traffic was extremely light. These fortuitous circumstances greatly helped limit the number of deaths and injuries.

As of February 14, there were a total of 58 deaths attributed to the earthquake. About 1,500 people were admitted to hospitals with major injuries,

another 16,000 or so were treated and released.

Estimates of the number of people temporarily or permanently displaced because of damage to their houses or apartments ranged from 80,000 to 125,000. Total loss from this earthquake was estimated to reach \$30 billion, the costliest earthquake in U.S. history.

Although the earthquake caused unprecedented damage and disruption, it also created an unprecedented opportunity to learn about earthquake mechanisms and effects. The earthquake triggered a historically high number of strong ground motion recordings. These recordings, coupled with wide-reaching damage surveys and analyses of specific structures, can provide a wealth of new insight into and understanding of earthquakes and their effects.

2. SEISMOLOGY AND GEOTECHNICAL EFFECTS

2.1 Seismology

The epicenter of the earthquake was located at 34°12'N, 118°32'W, about 30 km west-northwest of Los Angeles in Northridge (Figure 1). The focal depth was estimated at about 15-20 km (USGS 1994)

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1. National Institute of Standards and Technology
 2. Federal Highway Administration
 3. Department of Housing & Urban Development
 4. U.S. Geological Survey
 5. Federal Emergency Management Agency

and EERI 1994). The strong shaking lasted about 15 seconds in the epicenter area. The earthquake occurred on an unidentified fault. The fault had no distinct surface rupture.

Records from the main shock and aftershocks indicate that the rupture had a thrust focal mechanism, striking 10° north of west and dipping 30° to 45° south (Hauksson 1994, EERC 1994, and EERI 1994). Thousands of aftershocks were recorded in the following months; there were seven of them having a magnitude 5 or greater as of March 20.

Over one hundred strong-motion instruments were triggered by the event. In the epicenter area, peak horizontal ground accelerations approached or exceeded 1g in several locations (USGS 1994). Figure 2 shows the locations of selected peak horizontal and vertical ground acceleration recorded by the USGS's National Strong Motion Program. The Los Angeles Building Code specifies a design acceleration of 0.4g. An accelerograph recorded on the grounds of the Veterans Affairs Hospital in Sepulveda is shown in Figure 3. Note that the transient peak accelerations shown were each one-time events and not typical of the body of the shaking.

The high vertical accelerations recorded in numerous locations have induced discussions among the engineering community over the need to consider vertical accelerations in design. Currently, the model codes only require consideration of vertical accelerations in the design of cantilevered elements and post-tensioned horizontal elements, and those only in regions of high seismicity. In this event, a free-field vertical acceleration of 1.18g was recorded at Tarzana, about 6 km south of the epicenter, and maximums of about 0.6g occurred at several other locations.

2.2 Geotechnical Effects

The fracture of the thrust fault apparently did not reach the surface. No major surface faulting had been identified as of late March. Landslides, rock slides and slope failures were the most visible geotechnical effect caused by the earthquake. Soil liquefaction was widely reported, but apparently caused little structural or agricultural damage. Sand boils were reported along the Pacific coast from Mugu Lagoon to the north to the Port of Los Angeles

to the south, and inland in the epicentral area, near the junctions of interstate highways 5 and 210 and 5 and 405, and in areas around Simi Valley northwest of the epicenter (EERI 1994 and EERC 1994).

Liquefaction-related surface cracking and vertical offsets were reported at all sites where sand boils were observed. At other sites, such as the Jensen Filtration Plant in Sylmar and the nearby San Fernando Juvenile Hall, no sand boils were reported but lateral spreading and ground settlement indicate that liquefaction occurred. Minor breaks in water, sewer, and other pipe systems were widespread in areas of lateral spread and liquefaction.

3. BUILDINGS

The earthquake provided the first full scale "test" of modern (post 1970's) seismic building codes in this country. For the first time, a large and varied population of buildings was subjected to ground shaking equal to or exceeding that recognized in modern codes for design. The epicenter of the earthquake was located in a heavily populated urban-suburban area, the San Fernando Valley northwest of Los Angeles. In the epicentral region, most buildings experienced ground accelerations equal to or greater than that upon which the code design values are based.

The building damage caused by the 1971 magnitude 6.6 San Fernando earthquake in 1971 prompted significant revisions to earthquake design requirements. As a result, the 1976 Uniform Building Code (UBC) is often specified as a "benchmark" code that ushered in "modern" seismic design methods (FEMA 154, 1988). Comparisons of building response in the 1971 and 1994 quakes give some insight into the efficacy of earthquake mitigation practices that have been undertaken in the Los Angeles area in the intervening years.

The intent of building codes is to specify the minimum requirements needed for a structure to provide acceptable life-safety. Viewed in this light, the earthquake demonstrated the success of modern building codes. Of the 58 deaths attributed to the earthquake, 22 were caused by structural failures of buildings. The population of the three affected counties (Los Angeles, Ventura, and Orange) totals about nine million people. However, 80,000 to

125,000 people were made temporarily or permanently homeless because of damage to their homes and apartments. Schools, hospitals, offices, stores, and other commercial and industrial enterprises were forced to close due to damage, much of it nonstructural. Viewed in this light, the earthquake demonstrated the limitation of modern building codes. Because they do not include postearthquake serviceability requirements for most buildings, they do not ensure preservation of normal building function after an earthquake. Because they were not intended to prevent property damage in a large earthquake, economic losses can be high.

Building codes cover only new construction or changes to existing construction. The City of Los Angeles established a requirement that all unreinforced masonry buildings (URMs) larger than a specified size that were constructed prior to 1934 be assessed for seismic adequacy and, if necessary, be rehabilitated. This requirement, called "Division 88" led to the rehabilitation of all the older URMs, certainly helped reduce the life loss from this earthquake.

Buildings of all ages and types were damaged in the quake. However, it also should be noted that many buildings of all ages and types performed well. In the epicentral area, from the California State University, Northridge campus, to the Northridge Fashion Center mall, serious damage occurred. Several pockets of severe damage occurred at widely separated locations, such as downtown Santa Monica, along Ventura Boulevard in Sherman Oaks, downtown Glendale, and Hollywood Boulevard in Hollywood (Figure 4). The following sections present a few of the most spectacular damages resulted from the earthquake.

3.1 Northridge Meadows Apartment Complex

Collapse in a single apartment complex caused sixteen of the twenty-two deaths related to building failures. The Northridge Meadows complex, constructed in 1972, consisted of several three-story wood-frame buildings. About half of the units had open spaces for parking on the street level, typically around the perimeter of the complex. Most of the interior courtyard facing units had living space at the ground level rather than parking. About half of the buildings in the complex

collapsed. The first story gave way while the second and third stories remained largely intact. The sixteen people killed were in the first story apartments. All the buildings in the complex suffered some damage (Figure 5).

The apartment buildings were predominantly wood-frame, with wire mesh and stucco walls. Rows of steel pipe columns supported the upper stories along the building perimeter between parking bays (Figure 6). Transverse walls were typically spaced about every three parking bays. Longitudinal walls separated the parking areas from first story living spaces. The wire mesh and stucco coating on these walls provided insufficient resistance to the lateral earthquake forces generated by this earthquake.

The upper stories of the collapsed buildings were displaced laterally and in some cases came to rest offset by as much as three meters from their original locations. The steel pipe columns, which hinged at their bases, apparently controlled the distance of the offset as they bent to the ground (Figure 7). The Northridge Meadows building configuration, two stories of living space in a long, narrow building above one level of parking, is common in the San Fernando Valley. Many buildings of this type sustained serious damage, and some collapsed. These buildings were also built in the late 1960's or early 1970's, when use of stucco for seismic resistance in low-rise buildings was common. Current codes have essentially banned the use of this material.

3.2 Champagne Towers

Champagne Towers on Ocean Avenue in Santa Monica, a 16-story concrete apartment building, suffered serious damage. The condition of this building illustrates two classic examples of earthquake damage: damaged coupling beams between linked shear walls and shear failure of unintentionally short columns.

The transverse end walls are pierced by a single vertical row of window openings. The wall segments between the windows act as coupling beams linking the wall segments on either side. These beams suffered serious diagonal cracking (Figure 8). In the longitudinal direction, the lateral-force resistance is provided by concrete moment frames. The front of the building shows

no sign of damage. At the back, the columns and transverse wall ends are diagonally cracked (Figure 9). The solid infill railings which rise to about mid-height of the columns create an unintentional "short-column" effect, causing the columns to fail in shear. At the front of the building, metal pipe railings are provided at the balconies rather than solid infill, as at the back. This may partially explain why there is no apparent damage at the front of the building.

3.3 Hospitals

The original hospitals of Holy Cross and Olive View were badly damaged in the 1971 San Fernando earthquake. They were rebuilt following the requirements of the Hospital Act introduced by the State of California after the 1971 quake. The structural systems of these two hospitals performed well in the Northridge earthquake. However, damage to the sprinkler and chilled water systems at Olive View rendered the building temporarily unusable. At Holy Cross, damage to the air handling system forced closure of the hospital. However, St. John's Hospital in Santa Monica was closed due to structural damage. The 7-story northwest wing, which was built in 1952, had severe diagonal cracks in the piers between windows (Figure 10).

3.4 Bullock's Department Store

The collapse of large portions of the roof and floors of the 3-story concrete Bullock's department store at the Northridge Fashion Center could have caused more deaths than any other single building failure in this earthquake. Many multi-story columns were left intact as the concrete slab floors and roof fell on top of each to the basement, presumably due to punching shear failure of the slabs. The remaining-standing columns showed no evidence that slab reinforcement had been continuous through the columns (Figure 11).

3.5 Unreinforced Masonry Buildings

Reinforced masonry construction was introduced in 1934 after the 1933 Long Beach earthquake. Yet many pre-1934 unreinforced masonry buildings still exist today and all of them in the City of Los Angeles have been retrofitted with through-bolts

and face plates to connect the masonry walls to the wood floor and wood diaphragms, as required by the so called "Division 88 requirement (Figure 12). The City of Santa Monica doesn't have the same rehabilitation requirements, nevertheless, most, if not all URM's have been retrofitted with above-mentioned techniques.

Despite rehabilitation, many URM's in Santa Monica and in Hollywood were badly damaged. As a life-safety measure, rehabilitation was somewhat successful in this earthquake. However, rehabilitation was not successful at preventing damage; portions of buildings disintegrated, top stories and corners were particularly vulnerable (Figure 13). Such damages could present a real and serious threat to the safety of persons outside the affected building.

3.6 Kaiser Permanente Office Building and Barrington Building

The Kaiser Permanente office building on Balboa Boulevard in Northridge was badly damaged. The second story columns disintegrated, causing the upper stories to collapse onto the first story, which remained intact (Figure 14). The bare frame exposed by the damage suggests that the buildings had a strong-beam/weak-column configuration (Figure 15). The damage appears to have initiated at the joints.

The L-shaped concrete frame Barrington Building in West Los Angeles also had damage concentrated in the second story columns (Figure 16). The horizontal architectural panels stiffened the lower half of the columns at each story, creating a short-column effect.

3.7 The American Savings Bank Building

A steel-frame office building on the west side of Topanga Canyon Boulevard in Canoga Park, housing the American Savings Bank, experienced significant movement in its first story columns (Figure 17). A nearly identical building on the same site, oriented at right angles to the first, had only minor damage to glass at the first story. The first story column heights of the two buildings differed significantly: the ones in the undamaged building were considerably shorter than the ones in the damaged structure.

In the weeks following the earthquake, reports surfaced about a surprisingly large number of

damaged steel-frame buildings, which, as a class, have been viewed relatively earthquake-resistant. Failure modes reported include brittle fractures of column flanges, base plates, and welds at connections; and buckling of diagonal tube bracing (Los Angeles Times, 2/27/94 and EERI 1994).

3.8 Parking Structures

Eight major public parking structures suffered collapse or severe damage. Many other parking structures suffered less spectacular, but nevertheless serious, damage. The damaged parking structures were scattered throughout the affected area. A few key damaged structures are described herein.

California State University at Northridge Campus

The four-level garage was built in 1991 of precast concrete with cast-in-place concrete slabs. The lateral resisting system was an exterior perimeter frame constructed of precast "Trees" (columns with half-length beams cast as one piece) connected in the field to form a moment frame. The collapse apparently started at the interior of the building and the exterior perimeter frame was pulled over towards the center of the structure (Figure 18), suggesting that interior beams had lost their vertical support, causing the floor plates to collapse and pull the exterior walls in with them.

Kaiser Permanente Medical Complex on Cadillac Avenue

The five-level parking garage in West Los Angeles experienced a similar collapse. All four facades were pulled inward, suggesting that interior damage precipitated the failure (Figure 19). The garage was a post-tensioned, cast-in-place concrete structure with shear walls providing the lateral-force resisting system at the east and west ends, and moment frames at the north and south perimeter. The shear walls were cracked horizontally throughout their height due to the out-of-plane bending (Figure 20).

Trans World Bank Parking Structure

The two-level concrete parking structure adjacent to the Trans World Bank in Sherman Oaks had been seismically strengthened after suffering serious damage in the 1971 San Fernando quake. Flared extensions were cast next to the interior columns along their north-south axes (Figure 21), creating short wing walls supporting the precast beams.

The unrehabilitated exterior columns were badly damaged in the Northridge earthquake (Figure 22).

4. BRIDGES

4.1 Overview

The vast majority of bridges in the Los Angeles metropolitan area performed well in the Northridge earthquake. However, the quake caused the collapses of six major highway bridges and heavy damage to 157 other high bridges. The estimated cost to replace or repair these bridges is \$1.5B. Figure 23 shows the locations of the bridges inspected by the reconnaissance team. This section provides a brief description of field observations of several major bridge damages or collapses.

4.2 Interstate 5 (the Golden State Freeway) at Gavin Canyon Undercrossing

This bridge was designed in 1964 and constructed in 1967. It carries Interstate 5 over Gavin Canyon, about 3 km north of the intersection of Interstate 5 and State Route 14. An aerial photograph of the damaged bridge, after demolition had begun, is shown in Figure 24, and a ground level view is shown in Figure 25. The structure consists of two parallel bridges, with about a 66 degree skew alignment. Each bridge is composed of five spans. Each bridge has four two-pier bents, and there is a structural hinge near each of the two center bents. The superstructure consists of reinforced concrete box girders, and the central portion (between hinges) is post-tensioned. The bridge survived the 1971 San Fernando earthquake with virtually no damage. In 1974, the hinges were retrofitted with cable restrainers. The seat length at the hinges is 200 mm, which by current design standards would be considered inadequate, especially for a structure of this size and flexibility.

Despite the presence of cable restrainers at the hinges, failure of three of the four end spans of the bridge was apparently initiated by the spans falling off the hinge seats. The fourth end span, at the far western corner of the bridge, partially came off its hinge seat but did not collapse. After support was lost at the hinges, a triangular portion of three of the end spans collapsed. It is likely that the skewed alignment of the bridge was an important contributing factor in this failure. The skewed alignment

permitted rotation of the superstructure in a counter-clockwise direction, when viewed from above. The tall, flexible piers of the two center bents would have offered relatively little resistance to rotation in a horizontal plane. Rotation of the superstructure would have resulted in differential displacements at the hinges, and eventually unseating of the end spans at the hinges.

4.3 State Route 14 (The Antelope Valley Freeway) Interchange with Interstate 5 (the Golden State Freeway)

Two bridges partially collapsed at this interchange: the Route 14/5 Separation and Overhead Ramp C, which is the ramp linking westbound SR14 to southbound I5; and the North Connector Overcrossing Ramp M, which is the ramp linking westbound SR14 to northbound I5. In addition to the two collapsed ramps, there was evidence of pounding between spans at several hinges, and permanent differential offsets (both horizontal and vertical) were observed between the ends of the spans, as shown in Figure 26. The cable restrainers installed at hinges in this interchange during the early 1970's may have been responsible for preventing further collapses during the Northridge earthquake.

This interchange was designed in 1968 and was under construction in 1971 when portions were damaged by the San Fernando earthquake. At that time, one of the completed ramps in the interchange collapsed, and two ramps which were under construction were damaged. The portion which collapsed in 1971 was the South Connector Overcrossing, connecting southbound I5 with eastbound SR14. A photograph of the collapsed ramp, taken in 1971, is shown in Figure 27. This ramp was later rebuilt, with improved pier reinforcement, and it suffered no significant damage in the Northridge earthquake. The damaged portions of the other two ramps under construction in 1971 were repaired in place, but not strengthened; the portions not yet constructed were completed with limited seismic upgrading. Both of the ramps which partially collapsed in the Northridge earthquake were under construction at the time of the 1971 earthquake.

4.3.1 Route 14/5 Separation and Overhead Ramp C

This ramp was designed in 1968 and constructed in 1971. The structure consists of multiple-cell concrete box girders, most of which are post-tensioned, supported on single pier bents with flared tops. The portion of the ramp which collapsed was between Abutment 1 and the hinge located near Pier 4. A ground-level view of the collapsed span is shown in Figure 28, and a view of damaged Pier 3 is shown in Figure 29. The mode of failure of this ramp has not yet conclusively been determined, but the following scenario appears likely. Because Pier 2 was the shortest and stiffest pier in the structure, it probably attracted a large share of the horizontal seismic forces. The reinforcing details of the pier indicate that the pier contained quantities of lateral reinforcement which would be considered inadequate by current standards. Thus it is likely that Pier 2 was damaged and collapsed, pulling the superstructure off the seat at Abutment 1. It was reported that Pier 2 had completely disintegrated in the collapse. This observation is consistent with the conjecture that the pier was initially severely damaged in shear, and was then so badly weakened that it was crushed in compression. Following the collapse of Pier 2, a failure of the superstructure was initiated by excessive shear and negative bending moment at Pier 3. The superstructure sheared off on either side of Pier 3, leaving the pier standing nearly intact, as shown in Figure 29. The span between Piers 3 and 4 then collapsed, pulling the superstructure off the hinge seat near Pier 4.

4.3.2 North Connector Overcrossing Ramp M

This ramp was designed in 1968 and constructed in 1971. Photographs of the collapsed portion of the ramp are shown in Figures 30 and 31. The portion of the ramp which collapsed was located between Abutment 1 and Pier 3. This ramp was under construction in 1971 and was nearly completed when the San Fernando earthquake occurred, with only the portion from the hinge near Pier 8 to Abutment 11 remaining to be constructed. The portion of the ramp which collapsed in the Northridge earthquake, between Abutment 1 and Pier 3, was already constructed when the San Fernando earthquake occurred. Only minor damage to this ramp was reported following the 1971 earthquake (State of California, 1971). This damage consisted of permanent offsets at the hinges near Piers 4 and 6.

The collapse in the Northridge earthquake appears to have been initiated by the failure of Pier 2. After Pier 2 failed, the simply supported span between Abutment 1 and the hinge near Pier 2 collapsed, and, as shown in Figure 31, the superstructure failed in bending near Pier 3 due to a large negative moment. Pier 2 completely disintegrated, as shown in Figure 32. This is the shortest pier in the structure, so it is likely that it attracted a high level of lateral force, was damaged in shear, and finally collapsed in compression. Pier 10 is similar in height to Pier 1, but the quantities of lateral reinforcement in Pier 10 are greater than those in Pier 1. This is because Pier 2 had already been completed, but Pier 10 had not yet been constructed, when the 1971 earthquake occurred. Following the 1971 earthquake the plans for Pier 10 were revised to provide increased lateral reinforcement.

4.4 State Route 118 (The Simi Valley Freeway)

SR118 is the major east-west transportation route for northern Los Angeles County. The route passes just north of the epicentral region of the quake. A number of bridges along SR118 received minor, repairable damage, but two bridges were damaged severely: portions of a bridge collapsed at the intersection of San Fernando Mission Boulevard and Gothic Avenue; and nearby there was severe pier damage and a near collapse of the bridge at Bull Creek Canyon Channel. The performance of these two bridges is described below.

4.4.1 State Route 118 (Simi Valley Freeway) at San Fernando-Mission Blvd. and Gothic Ave

Because the Mission-Gothic Undercrossing was designed in 1972, after the San Fernando earthquake, the bridge contains seismic details which are improved over the details used in designs of the 1960's and earlier. Most notably, the spiral hoops in the bridge piers are spaced closely together. Nonetheless, the piers of the Mission-Gothic Undercrossing suffered severe damage in this quake, and one of the two parallel spans partially collapsed. Damage to piers at Mission-Gothic is shown in Figures 33 and 34. In addition to pier damage, there was also severe damage to the abutments, including cracked wing walls, settlement of soil behind the abutments, and

apparent shifting of the abutments.

The likely failure mode of the bridge was that the piers initially suffered severe shear damage, followed by crushing of a number of piers in compression. The structure may also have shifted to the southwest, as constrained by the geometry of the abutments. Although unseating at Abutment 5 did occur, this was probably a secondary effect, as the seat lengths were generous by current standards. Rather, failure was probably initiated by damage to the piers. In this case the failure of piers has important theoretical implication, as the piers of this bridge contained quantities of lateral reinforcement similar to those required by current seismic design standards. Therefore, further research will be required to determine why the pier reinforcement was inadequate in this case.

4.4.2 State Route 118 (The Simi Valley Freeway) at Bull Creek Canyon Channel.

The bridge did not collapse completely, but many of the piers were severely damaged, as shown in Figures 35 and 36. In addition to pier damage, there was significant damage to the abutments, including cracked wing walls, settlement of soil behind the abutments, and possible shifting of the abutments.

This bridge was designed just after the 1971 San Fernando earthquake, so it contains some seismic detailing which is improved over earlier bridge designs. However, since it was not until several years after the San Fernando earthquake that seismic design codes for bridges were significantly changed, the design of this bridge would be considered substandard by current design codes.

All ten of the piers in Bent 3 failed in combined shear and compression near their bases, as shown by Figures 35 and 36. In Bent 2, Piers on the south side of the span failed near their top end, and the damage became progressively less for piers to the north in Bent 2. The farthest north piers in Bent 2 showed relatively little damage - only diagonal shear cracks near the base, with no spalled concrete. This uneven distribution of damage to piers was probably caused by the asymmetric plan geometry of the bridge.

The confining reinforcement in the piers is inadequate by current standards. All pier failures occurred in

the zone of wide spiral spacing. Another factor contributing to pier failure was that the effective lengths of the piers were much shorter than the distance between the footings and the girder soffit. The lengths of piers varied between roughly 6000 and 9100 mm. In Bent 2, the effective pier lengths were decreased roughly one-third by compacted backfill soil above the pier footings. In Bent 3, the pier lengths were also decreased roughly one-third, but by a reinforced concrete channel liner wall, which was cast abutting the piers. The shortened effective pier length resulted in stiffer piers, which were more susceptible to shear-dominated failure than bending-dominated failure.

4.5 Interstate 10

Interstate 10 is a major east-west artery running between Santa Monica and downtown Los Angeles. The freeway was constructed in 1966. Major bridge collapses occurred at two locations: the La Cienega Blvd.-Venice Blvd. Separation and the Fairfax Ave.-Washington Blvd. Undercrossing.

4.5.1 Interstate 10 La Cienega Blvd./Venice Blvd. Separation

Figure 37 is a ground-level view of the portion of the westbound lane that collapsed to the ground at the hinge located between Bents 7 and 6. The pier in the foreground is the northernmost pier of Bent 7. It is seen that there was extensive column shortening due to the failure of the lateral reinforcement to provide adequate confinement of the core concrete. Fractured lateral reinforcement can be seen to the right of the failed portion of the pier. Figure 38 shows the other two piers of Bent 7 which supported the westbound lane. Extensive failure and column shortening is evident. The concrete block wall behind the piers is part of a storage building that was constructed beneath the bridge structure. The storage building extended from Venice Blvd. to La Cienega Blvd. The piers of Bent 7 which supported the eastbound lane suffered relatively minor damage, and the roadway to the east of Bent 7 remained largely at its original elevation.

Figure 39 shows the northernmost pier of Bent 6, located just to the west of the hinge. This pier totally disintegrated, but the storage building prevented the roadway from collapsing to the ground. Figure 40 shows the southernmost pier supporting the

eastbound lane at Bent 3. The top of the pier is severely damaged and it is likely that the storage building prevented the total collapse of the roadway.

In summary, the bridge structure spanning La Cienega Blvd. and Venice Blvd. was extensively damaged. The failure is attributed to the small amount of lateral pier reinforcement. As the piers cracked due to the lateral loading, the lack of adequate confinement resulted in a reduction of the vertical load capacity because of core concrete loss and buckling of the longitudinal bars. Had it not been for the storage building located beneath the bridge, it is likely that more spans would have collapsed to the ground.

4.5.2 Interstate 10 Fairfax Ave.- Washington Blvd. Under Crossing

The earthquake caused partial collapse of two spans of the eastbound and westbound lanes on either side of Bent 3. The piers in Bent 3 had failed and caused the girders to sag at this location. However, cable restrainers at the hinge west of Bent 4 prevented the girders from falling off of the hinge seats (Figure 41). Figure 42 shows the westbound lane of I10 over Fairfax Ave. It can be seen that the piers in Bent 3 shortened and caused the girder to sag. It can also be seen that the span to the west of Pier 2 lifted off of the abutment. Figure 43 is a close up view of one of the piers in Bent 3. The failure mode is similar to that observed at Venice Blvd. and La Cienega Blvd. When the piers were subjected to lateral ground motions, the lateral reinforcement was not able to adequately confine the core concrete. As a result of lateral load damage, there was a loss of axial load capacity and the piers shortened under the action of the vertical loads. As mentioned, the piers at Bent 4 had considerably more longitudinal reinforcement than the other piers. Examination of the piers in Bent 4 revealed varying degrees of diagonal cracking and spalling of the concrete cover. At the time of the site visit, these piers were surrounded with wooden shoring as a precautionary measure during the demolition of the collapsed spans.

5. LIFELINE SYSTEMS

5.1 Introduction

Lifelines include water, sewer, gas, fuel, electric power, telecommunications, and transportation

systems. These systems are critical to the vitality of the built environment and the functioning of modern society. They provide services to the community to maintain its safety, health, financial transactions, and to stimulate economic activities. Damaged lifelines can impede emergency response following an earthquake, and can hinder postearthquake recovery. Disruption of regional lifeline systems due to a major natural disaster such as an earthquake can have a profound effect on the entire nation because of the economic interdependence of lifeline systems and the functions they support.

This section offers a brief overview of the performance of lifeline systems, including observations made by many investigators, but with particular emphasis on the sites that the team visited personally.

5.2 Water Supply Systems

In addition to limited sources from the region's local groundwater basins, the main water supply is from Northern California and the Colorado River. January 17, 1994 was the first time in history that an earthquake resulted in the breakage of all four pipelines that feed water to the region's three water treatment facilities.

Compared with the extensive damage caused by the 1971 San Fernando earthquake to the Jensen treatment plant in Sylmar (under construction at the time), the 1994 earthquake caused only minor damage. The 1994 damage included lateral spreading of the ground or soil settlement around the facilities, leaks in pipelines, and leaks at construction joints.

While water supply to these facilities was available once the major pipelines were repaired, the system nevertheless failed to provide water to customers because of the failure of the water supply distribution network, especially the network serving areas near the epicenter. Thousands of main line leaks were reported and the repairs were very time-consuming.

Among the numerous situations that contributed to the disruption of the water supply system was damage to one of the four damaged pipelines, Los Angeles Aqueduct No. 2 at Terminal Hill. Aqueduct No. 2 is made of 2.1-m diameter steel pipes. Terminal Hill is located about 20 km north-northeast of the epicenter, southeast of the intersection of I-5 and SR14. There

is no strong motion record available for the site. However, two stations maintained by the California Division of Mines and Geology (CDMG) and the U.S. Geological Survey (USGS) about 5 km south of the site showed peak ground accelerations over 0.9g.

A steel pipe brings water up from the canyon below (Figure 44). The pipe is supported on concrete saddles built along the mountain slope. In a few places, the pipe separated from the saddles creating 50 to 80 mm gaps. In at least one location, the pipe crashed into the saddle. In two other locations, the pipe sections bulged 80 mm and 150 mm respectively. However, no rupture or leakage was noticed. The ruptured section of the 2.1-m pipe is located near top of the hill. The two sections where the rupture occurred were connected together using a mechanical coupling system (Figure 45). To restrain the relative movement between the two pipe sections during strong shaking, the sections were connected by eight pairs of restrainer rods 35 mm in diameter and 2.2 m long. The rods were attached to brackets, which were welded to the pipes. These welds broke due to strong shaking and resulted in the separation of the two pipe sections.

Repair of the pipe sections began immediately after the earthquake. The repair work was completed in the evening of January 19 and the aqueduct started operation at 2:00 a.m. January 20. However, leakage was found shortly thereafter which caused the operation to shut down again. Excavation was required to repair two other sections. The pipeline was back in operation on January 21.

There were numerous breaks of water lines during this earthquake. Two water mains were ruptured at a site along Balboa Boulevard adjacent to the rupture of a 0.6-m gas main. A major fire resulted, which is described later in this section.

5.3 Gas and Liquid Fuels

Natural gas systems consist of transmission, distribution, and service lines. In the earthquake-affected area, transmission lines are steel pipes with diameters ranging from 0.3 to 0.8 m. Most of the failed lines were of pre-1971 construction. The distribution lines are either steel or plastic pipes. Compared with the effects of the 1971 San Fernando earthquake, this earthquake resulted in more ruptures in the distribution lines than in the

transmission lines. Most of the breaks occurred to old steel pipes. Plastic pipes used in the distribution system seemed to perform well.

As happened in earlier earthquakes such as the 1987 Whittier Narrows earthquake and the 1989 Loma Prieta earthquake, tens to hundreds of thousands of gas supply outages occurred. Most outages were the result of customers shutting off gas valves because of fear of gas explosions or fires. While immediate safety is the intent of this action, it can result in a long delay before service is restored because gas company technicians must test each system before turning the valve back on.

The rupture of a 0.6-m gas main occurred along Balboa Boulevard between Rinaldi Street to the south and Lorillard Street to the north, about 0.5 km north of the intersection of Balboa Boulevard and SR118 (Figure 46). Along this stretch, compressional ground failures occurred between Rinaldi Street and Halsey Street, and extensional ground failures occurred between Bircher Street and Halsey Street.

Three pipelines ruptured as the result of ground contraction; a 150-mm gas distribution line, the 1.8-m Rinaldi trunk water line, and a 0.6-m gas main (Figure 47). The Rinaldi trunk line was of post-1971 construction and the gas main was of 1930 vintage. These pipes showed a shortening of 125 to 150 mm.

About one block north, the ground extension caused rupture of the same 0.6-m gas main and a 1.2-m water main (Figure 48). The rupture of the gas main caused a major fire at the site that destroyed five houses (Figure 49). The loss of both water mains at this location and the difficult access to the site due to the fire and flooding in the street made fire fighting difficult.

An excavated section just north of the fire site revealed some additional underground lines (Figure 50). The 460-mm crude oil line in the middle of the photo performed well. The 150-mm gas distribution line shown is a replaced section.

In addition to the above damage in the epicentral area, the strong shaking from the earthquake cracked welds at several locations along a 250-mm pipeline transporting crude oil to refineries from the San Joaquin Valley. As a result there was an oil spill along the Santa Clara River.

5.4 Electric Power

Power was lost to most of the Los Angeles basin area after the earthquake. Nearly 2 million customers were out of service immediately after the quake. About half of them had power restored within one day and over 95 percent had power restored by midnight Tuesday, January 18. All power was restored within ten days after the earthquake.

Some transmission towers suffered significant damage, many as the result of foundation failure. Damage to several high voltage substations near the epicenter, such as Sylmar, Pardee, and Rinaldi, led to the widespread power outage in the Los Angeles basin, as well as the isolated outages throughout seven western states (Figure 51). As happened during the 1971 San Fernando earthquake, porcelain elements of equipment of 230 kV and 500 kV classification suffered the most damage (Figure 52). This highlights the urgent need for developing new materials that would be more earthquake resistant to replace porcelain, which is very brittle. Furthermore, most of the 230 kV circuit switchers, similar to those in the forefront of Figure 53, at the Sylmar substation, were damaged. However, none were damaged during the 1971 earthquake, a possible indication of much stronger ground shaking by the Northridge earthquake. Most of the capacitor banks, similar to those in the background in Figure 53, performed well in this earthquake, whereas most collapsed during the 1971 quake. Better performance of the capacitor banks is the result of higher seismic requirements in equipment qualification and in installation practices.

The level and types of damage to electrical systems experienced in the Northridge earthquake demonstrate that many valuable lessons have been learned since the 1971 earthquake. Many improvements have been made in areas such as requirements for equipment qualification and installation practices.

5.5 Transportation

All airports in the region survived the earthquake with no major problems. The airports were shut down immediately after the quake as a precautionary move to allow for the inspection of runways and taxiways. All airports were re-opened for operation once the inspections had been completed. No structural damage was observed in airport facilities.

However, they did suffer some typical types of non-structural damage, such as fallen ceiling tiles and leakage of water pipes.

There was a freight train derailment in Northridge during the earthquake (Figure 54). The 64-car freight train belonged to Southern Pacific and was on its way from Houston to Sacramento. Twenty-five cars derailed, sixteen of which carried sulfuric acid or diesel fuel. The derailment resulted in the spill of 30,000 liters of sulfuric acid and 7,500 liters of diesel fuel. There were no casualties in this incident. About 200 m of railroad tracks were replaced immediately following the earthquake and rail service was restored at 2:00 a.m., January 19. Removal of damaged cars and cleanup of debris were completed on January 21.

Strong ground shaking and lateral movement of subgrade materials resulted in numerous ruptures of asphalt pavement and concrete sidewalks in the epicentral area (Figure 55). In some instances, local traffic was interrupted temporarily waiting for the repair of these cracks. In most cases, the damage was minor and local traffic was not interrupted. The south approach of Balboa Boulevard at SR118 caved in from loss of abutment fill due to a water main break. This bridge was closed for traffic due to some structural damage to the piers and the loss of the south abutment fill.

6. POSTEARTHQUAKE FIRES

6.1 Introduction

The Northridge earthquake resulted in fires which challenged the resources of the fire service due to the number of fires, disruption of the water supply, and damage to fire protection systems within buildings. The majority of the estimated 30 to 50 significant fires were located in the San Fernando Valley and confined to the building of fire origin either by separation or by fire department action. Fortunately there was no loss of life from fire. A principal cause of the fires involved natural gas leaks. A small number of fires were caused by hazardous chemical interactions. The only major instances of building-to-building fire spread occurred in three manufactured housing developments (mobile home parks). Fire incidents occurred at a greater than normal rate in the days following the earthquake with the cause of some of the fires directly attributable to

the restoration of power and gas to buildings shaken in the initial earthquake and aftershocks. Fire sprinkler systems sustained damage in some buildings although the number and extent of damage is not known at this time.

Fire protection in the municipal environment is derived from private and public systems including building construction, building fire protection systems, land use, public and private water supplies, public and private fire departments, and communication and utility systems. In the aftermath of a major earthquake the normal interactions between these systems is disrupted. Even though emergency operational plans exist, the interaction between these systems in reducing the loss from fire is complex since it involves decisions on the part of a great many people.

The loss of life and property caused by fire occurs in a different time frame than the structural and property damage caused directly by the earthquake. While most of the loss caused by shaking occurs during the time of ground movement, there is basically no fire loss during that time. Fire loss directly attributable to the earthquake begins immediately following the earthquake and can continue for days after the ground movement has stopped.

This section examines the factors contributing to the cause, spread of and loss from fire in selected buildings affected by the earthquake.

6.2 Fire Events Following the Earthquake

Immediately following the earthquake the Los Angeles City Fire Department initiated the Earthquake Operational Mode which included placing emergency equipment on patrol throughout the city and dispatching fewer pieces of equipment to each incident in order to accommodate the increased number of incidents. Earthquake damage was wide spread but occurred mostly within the City of Los Angeles and most of the fire incidents were within the San Fernando Valley. Immediately following the earthquake electrical power was lost and telephone service disrupted throughout the city. At 0545 hours Mayor Riordan declared a state of emergency and by 0645 as many as 50 structure fires had been reported and over 100 incidents were being handled by the fire department. By 0945 all fires were under control.

Although the earthquake was centered within the City of Los Angeles, there was damage in surrounding counties and emergency resources throughout the region were utilized. In addition to responding to fire incidents, the fire department provided emergency medical, hazardous materials, and urban search and rescue services. The Los Angeles City Fire Department responds to over 900 fire, medical, and other emergencies on a typical day. This number increased to over 2200 on the day of the earthquake and remained at twice the normal level in the following days. The continued high number of incidents was due in part to fires associated with the restoration of utilities.

Water available for fire fighting was generally adequate in the San Fernando Valley area during the day following the Earthquake. The exceptions were in areas near the boundaries of the system and in areas at higher elevation. In the hours following the earthquake pressure in the water system dropped due to disruptions in supply and more than 3000 leaks. By the day after the earthquake, water tankers had been deployed throughout the San Fernando Valley to assist in fire fighting operations. On January 20th fire department pumpers were used to pump water from areas of adequate pressure within the system to areas with low pressure.

6.3 Fire Causes

The 30 to 50 fires reported initially following the earthquake occurred in a variety of residential and commercial occupancies. The majority of buildings in the San Fernando Valley are four stories or less in height and therefore the fires occurred primarily in these types of buildings. Figures 56 to 59 show some examples of buildings involved in postearthquake fires. The fire in the rear of the apartment complex shown in Figure 59 was the only fire observed in completely collapsed portion of a structure.

Preliminary indications are that a significant number of fires were associated with natural gas leaks. Natural gas is not in itself a source of ignition but it is relatively easy to ignite especially in confined spaces. Natural gas is the predominant fuel used for space and water heating in the Los Angeles area. Although electrical power was lost throughout the area immediately after the earthquake, the most likely source of ignition was a combination of electrical

sources and flames in the gas appliances themselves. Gas leaks occurred both inside and outside of buildings. The fire resulting from a leak in a gas main under a street destroyed several nearby houses. Figure 60 shows a gas meter in a manufactured housing development (mobile home park) in which there were at least six individual ignitions. Although there was not a leak in the gas service shown, it demonstrates how the movement of the manufactured homes following the earthquake damaged the gas service resulting in leaks which were ignited by unknown sources. There were no postearthquake fires in the newest section of the development where an improved gas service design was used. As in past California earthquakes, water heaters appear to be a source of gas leaks (Mohammadi, et al, 1992). Inadequately secured water heaters are the gas appliance most likely to tip over during an earthquake. The fire which destroyed the multi-family housing unit shown in Figure 61 was reported to have started as the result of damage to a water heater. An undamaged housing unit similar to the one which was destroyed can be seen in the background. Even though natural gas leaks may have played a role in a significant number of the 30 to 50 reported fires, this number is very small when compared to the total number of buildings exposed to significant shaking as a result of the earthquake. Since residents of this area are aware of the dangers of gas leaks following an earthquake many fires may have been averted by individuals shutting off the gas to buildings or appliances.

The rapid failure of the electrical power distribution system probably resulted in fewer fires than might have been expected. As electrical and gas service was restored in the days following the earthquake a significant number of fires were reported. Some of these fires were a result of earthquake damage to electrical and gas equipment which went unnoticed or unattended. Electrical and gas service was not disconnected in all red tagged buildings which were identified by authorities as unsafe to enter. These and additional fires may have all occurred immediately following the earthquake if electrical service had been maintained.

As in past California earthquakes, a small number of fires appear to have been caused by flammable liquid or chemical spills. Figure 62 shows a science building at the California State University at Northridge in which the fire was reported to have

been the result of a chemical spill. No fires were known to have occurred at service stations. Since the earthquake occurred when most people were asleep, fire causes such as overturned candles and barbecue grills and fires associated with industrial processes appear to be nearly nonexistent.

A small number of wildland fires were attributed to earthquake related causes, most likely arcing in overhead power lines. Since the wind was light and the vegetation was not excessively dry, these fires were easily extinguished.

6.4 Performance of Fire Protection Systems

Some damage to fire sprinkler systems has been reported but the full extent is not known. Damage to these systems is frequently the most visible of the fire protection systems since it may result in water leaks. Interviews with persons who have entered buildings in the earthquake area indicate that many sprinkler systems remained intact particularly those installed in accordance with latest seismic standards. Typical damage to fire sprinkler systems included broken pipes due to differential building movement or the sway generated in long pipe runs without adequate bracing. Sprinklers installed in the downward or pendent position from piping above ceilings were in some cases sheared off.

In other cases pendent sprinklers installed in drop ceilings were pulled through the ceiling by the upward movement of the pipes and punched new holes in the ceilings during the downward movement. While the punching may not have resulted in leaks, it damaged the sprinkler deflectors which generate the desired spray pattern.

Damaged deflectors usually result in a significant decrease in sprinkler performance requiring the sprinklers to be replaced.

Sprinkler systems normally have one or more check valves which prevent water from flowing from the sprinkler system into the water supply system. In the most common wet pipe system, the pressure in the sprinkler system piping will be the highest pressure attained in the water supply system over time. In the days following the earthquake, as the fire department pumped water from one part of the municipal water supply system to another, there were significant local

increases in pressure. These higher pressures were then "trapped" in the sprinkler systems. Although it is probably not a major problem and can easily be remedied by bleeding off the pressure, these higher pressures could lead to premature failure of the system and reduced effectiveness at the time of activation until the system returns to the design pressure.

Damage to fire alarm, detection, smoke control, other extinguishing systems, and passive building fire protection systems such as fire and smoke barriers has not been reported at this time. The disruption of land based communication systems is reported to have affected the ability of systems to dispatch alarms.

7. CONCLUSIONS

7.1 Introduction

The Northridge earthquake caused severe damage to a wide range of structural types because the epicenter was located in a populated urban area. Damaged structures revealed a number of deficiencies in current construction practices and areas needing improvements in code provisions. Implementing lessons learned about structural performance and postearthquake fires will reduce seismic hazards throughout the United States.

7.2 General

- The Northridge earthquake claimed 58 lives and caused over 1500 serious injuries. However, fewer than half of the deaths were attributed directly to structural failures. Because it occurred at 4:31 a.m., on a holiday, life loss was limited to a small number. Had the earthquake occurred during business hours, the collapse of parking structures alone could have caused a large number of deaths.
- Although a number of fires started immediately following the earthquake, calm winds limited spreading of fires in residential and commercial districts. At mobile home parks, fires spread from unit to unit. In most instances, fires were caused by natural gas leaks.

- Damage to multi-family dwellings contributed significantly to the over 25,000 dwelling units that became uninhabitable. Providing adequate shelter for displaced persons is a major task after an earthquake. Special attention should be paid to improving the seismic performance of existing dwelling stock.
- At many locations, peak ground acceleration exceeded 0.4g, the maximum design value in building codes. However, most buildings met code expectations for performance. Because many strong motion records and response measurements are available from this earthquake, valuable opportunities exist for in-depth studies of building performance to assess the adequacy of design values for earthquake forces and provisions for seismic resistance.

7.3 Building Performance

- In many cases, buildings designed and constructed in accordance with modern (mid-1970's or later) seismic requirements performed well structurally. This clearly shows the value of incorporating modern seismic design and construction requirements into building codes. However, failures of structures characterized as "Undefined Structural Systems" (UBC 2333(i)2), such as the parking garage at California State University at Northridge, indicate that the performance of such structural systems needs to be evaluated carefully to update code provisions.
- Damage to unreinforced masonry (URM) buildings was widespread. In most cases, those URM buildings rehabilitated with parapet braces and floor-wall ties, as those rehabilitated in response to the Los Angeles division 88 ordinance, escaped total collapse. However, walls sustained severe cracking and, in many cases, pieces fell onto sidewalks. This posed life-threatening hazards to pedestrians.
- Nonstructural damage caused hospitals, schools, businesses, and industrial facilities to be inoperative even though structural

damage was minimal or non-existent. An in-depth review of current code requirements and standards for nonstructural elements is needed to improve their seismic performance.

- Damage to steel structures was not readily visible from the exterior of buildings because most steel members are hidden behind architectural finishes and fire proofing. Removal of such coverings revealed brittle failures of welds and connections in many steel frame structures. Because owners of damaged structures often wish to keep damage reports confidential, damage information is not forthcoming. Detailed failure analyses of available data should be performed to understand the underlying causes of these failures.

7.4 Bridge Performance

- In general, bridges designed using standards developed after the mid-1970's performed well. Several bridges near the epicentral region, which were designed and constructed in the 1960's and early 1970's, sustained severe damage. Of the seven major bridges which sustained severe damage, six failed due to inadequate lateral reinforcement of the bridge piers.
- Most older bridges which had been seismically retrofitted (with cable restrainers, pier jacketing or foundation strengthening) performed well in the Northridge earthquake. However, because this earthquake was relatively moderate in magnitude, it should not necessarily be concluded that all seismic retrofit methods for bridges have been adequately proof tested by this event. Design criteria for cable restrainers may need to be reviewed. Even though jacketed bridge piers apparently performed well in this earthquake, it would be valuable to study the intensity of ground motions experienced at the specific bridge sites where jacketed piers have been employed, so that the performance of jacketed piers in larger events can be estimated.

- It is likely that some bridge piers were damaged because their effective lengths had been reduced. Several factors reduced the effective lengths: architectural flares at the tops of piers; backfill soil over a portion of the pier height; and concrete walls cast integrally with, or directly abutting, piers. Such constraints need to be minimized, or the effects of the constraints must be considered carefully in the design of piers.
- In bridges with piers of varying heights, the shortest piers tended to sustain the most damage. This is apparently because short piers have high lateral stiffnesses, and therefore attract a large share of the seismic loads. A better understanding of the role of short piers in overall bridge performance, is needed.
- Bridge spans which had skewed alignments or irregular plan configurations often sustained severe damage. Special attention should be paid to the potential for problems with bridges having skewed alignments or irregular plans.
- Older bridge bearings, of the steel rocker type, are highly susceptible to damage during strong ground shaking. Loss of rocker bearing support can lead to a broad range of bridge damage, including cracked girders, loss of roadway elevation alignment, and complete collapse of the superstructure.

7.5 Performance of Lifelines

- Damage to older trunk lines and main lines for water distribution caused serious disruptions in water supply in the epicentral region. About 50,000 Los Angeles Department of Water and Power customers were without water on the first day after the earthquake. About 10,000 customers were still without water one week after the earthquake.
 - Buried pipelines which carry natural gas and oil fractured at many locations due to ground motion. Over 1300 breaks and leaks in the gas piping system were reported.
- As in the past earthquakes, brittle ceramic elements, which are often the weak links in circuit breaker assemblies, were damaged.

7.6 Fire

- The occurrence of the earthquake before the start of morning traffic on a federal holiday allowed the fire department to respond to fires promptly without delays.
- Damage to natural gas pipelines and appliances resulting in leaks contributed significantly to postearthquake fires.
- In many cases, electric power was restored to buildings which were identified as unsafe for entry. The desire to restore utility service as quickly as possible is at odds with the desire not to cause fires.
- In general, fire sprinkler systems designed and installed in accordance with the latest seismic standards withstood the earthquake with little damage. However, in some instances, sprinkler pipes ruptured where sprinkler systems interacted with suspended ceilings.

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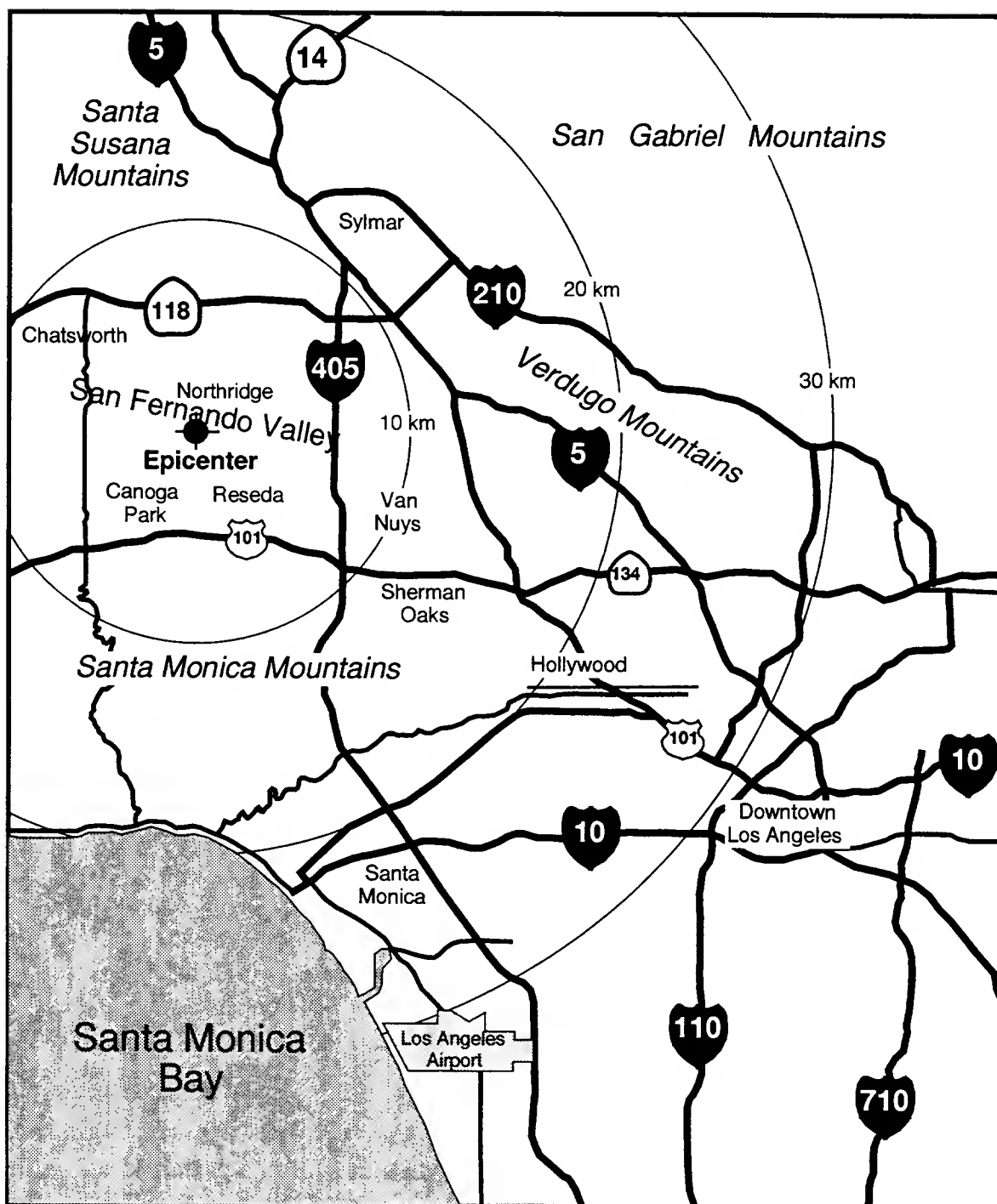
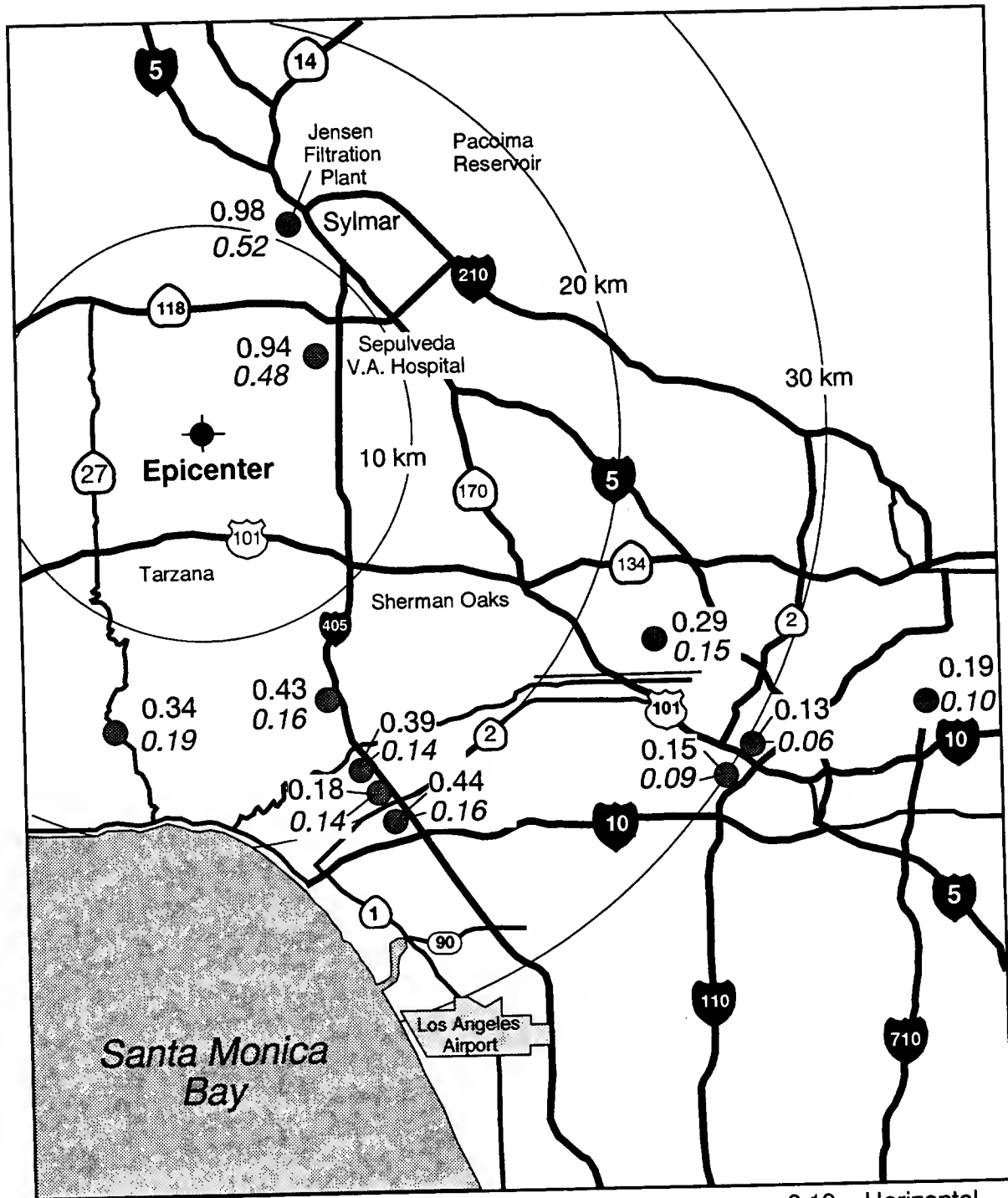


Figure / The epicenter of the January 17, 1994 Northridge earthquake was centered about 30 km northwest of Los Angeles in the San Fernando Valley.



Source: USGS

Legend: ● 0.13 = Horizontal
0.06 = Vertical

Figure 2 Peak horizontal and vertical ground accelerations recorded at some of the instruments in the affected area operated by the USGS's National Strong Motion Program.

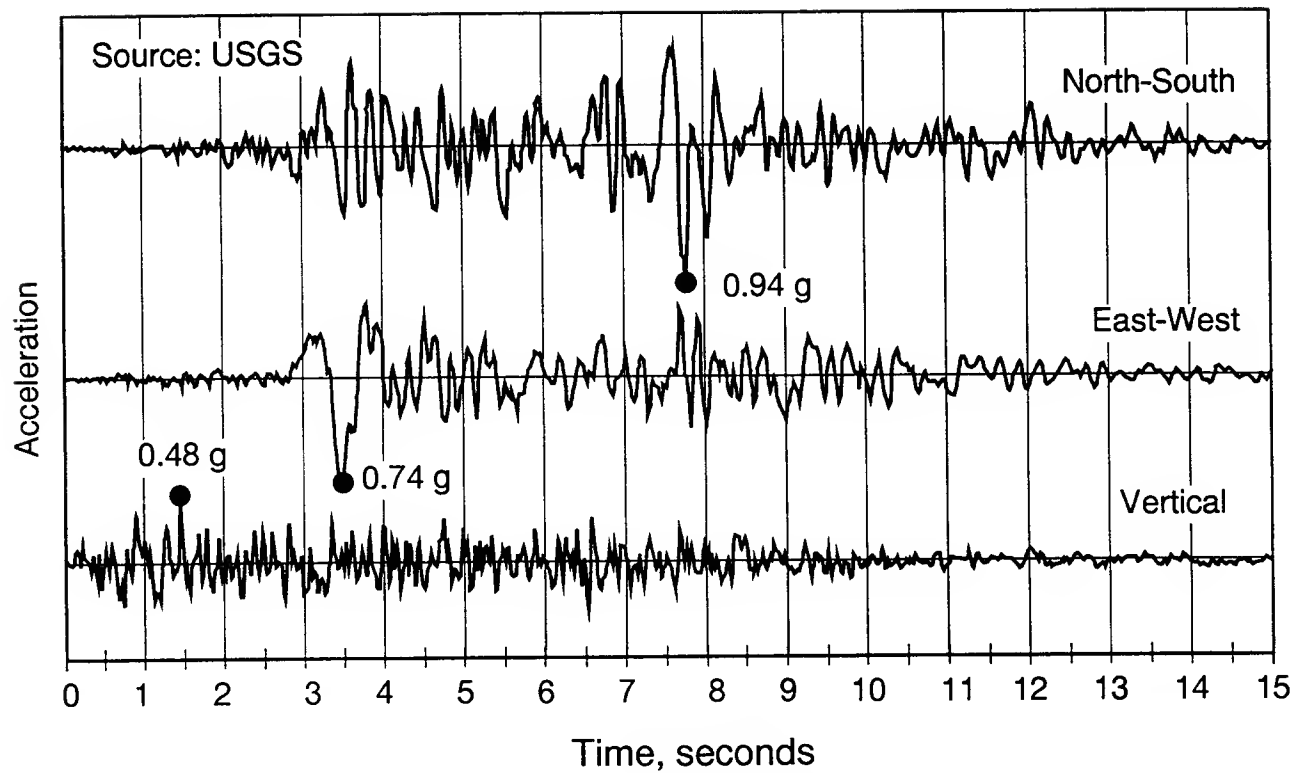


Figure 3 Accelerograph record from the grounds of the Sepulveda Veterans Affairs Hospital, 7 km from the epicenter.

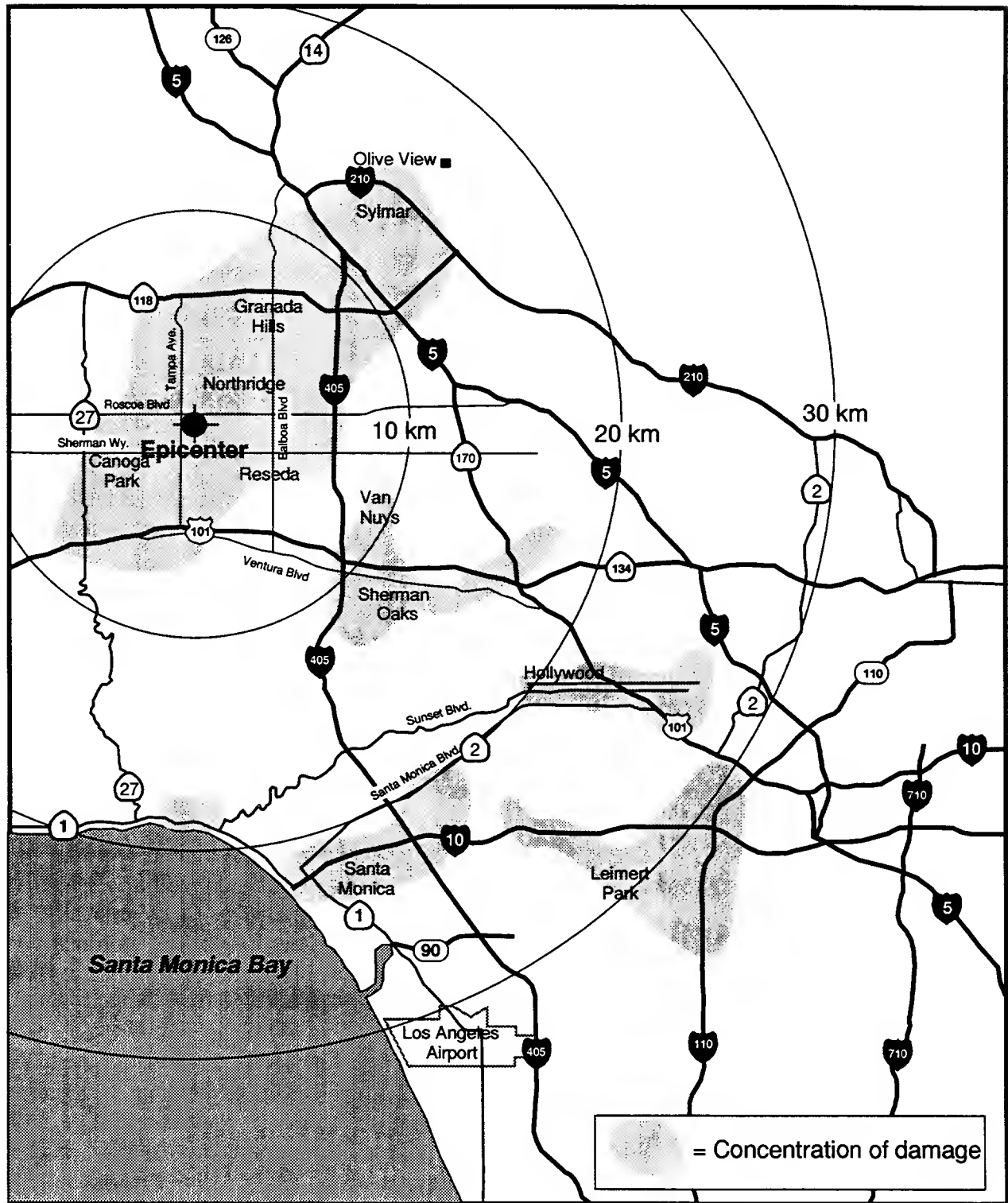


Figure 4 Serious damage to buildings caused by the magnitude 6.8 Northridge earthquake was widespread, but, outside of the epicentral area, seriously damaged buildings tended to occur in pockets.



Figure 5 At the Northridge Meadows apartment complex near the epicenter the first story in several of the buildings collapsed, killing sixteen people. The second and third stories remained essentially intact. Large portions of the first story in these buildings were open space for parking. This type of collapse occurred in a significant number of similar apartment buildings throughout the affected area.

Figure 6 Steel pipe columns between parking bays supported the upper stories of the Northridge Meadows apartment buildings. Few of the buildings in the north half of the complex collapsed, but all were damaged.



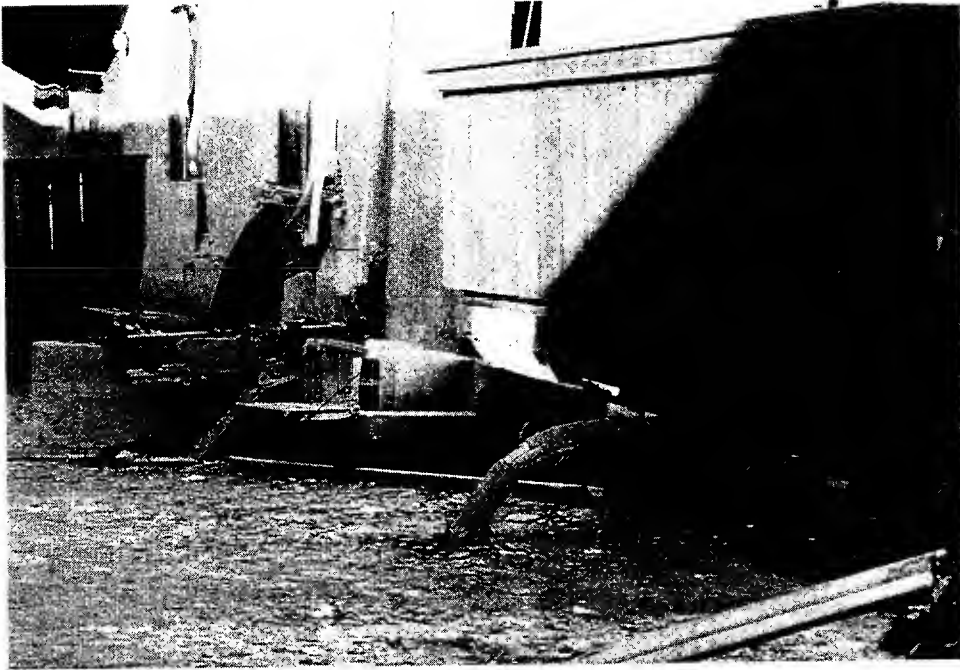
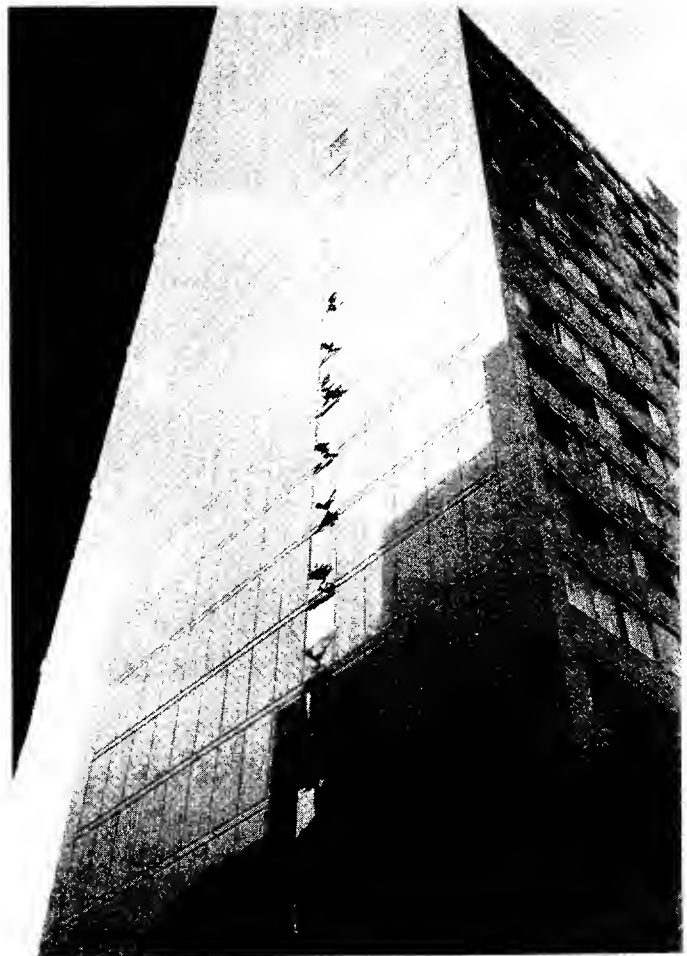


Figure 7 At Northridge Meadows, the first story steel pipe columns generally hinged near their bases but retained their length, controlling the displacement of the upper stories.

Figure 8 Champagne Towers apartment building in Santa Monica suffered a classic form of earthquake damage: shear failure of the coupling beams between linked shear walls at the transverse end of the building.



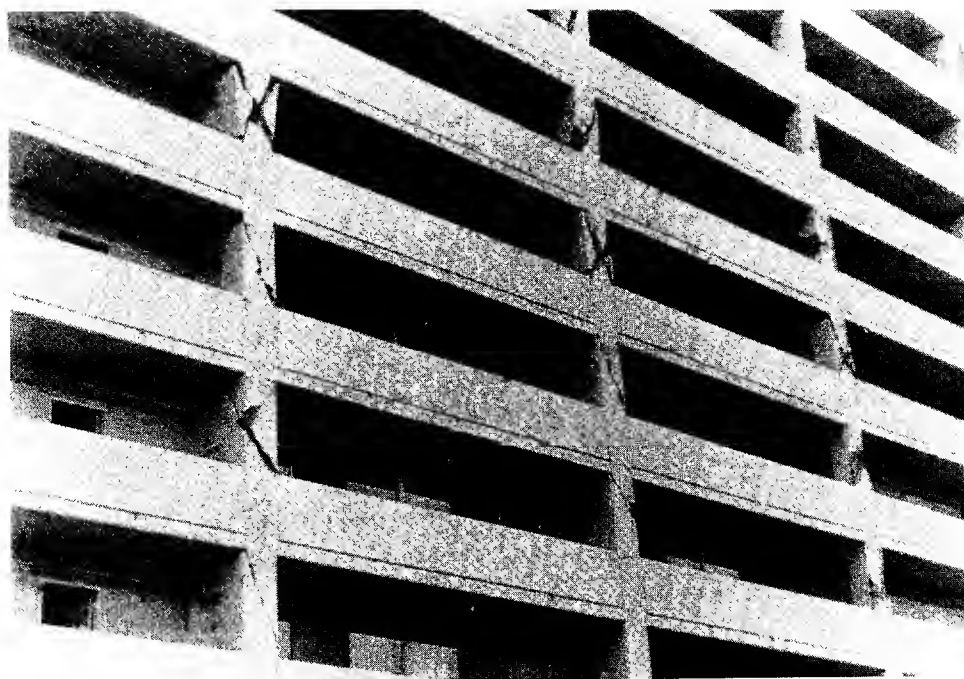


Figure 9 The back of the Champagne Towers building was badly damaged. The railings here are solid infill, which effectively stiffen the lower half of the columns. The shortened upper half of the columns were forced to accommodate all the displacement, and they failed in shear.



Figure 10 The seven-story northwest wing of St. John's hospital in Santa Monica experienced severe X-cracking in the piers between the second story windows.

Figure 11 A portion of the concrete waffle slab roof and the interior floor slabs at the Bullock's department store at the Northridge Fashion Center mall fell to the basement, leaving many of the columns standing. No reinforcing steel can be seen in the remaining columns that would have connected the columns to the floor slabs.

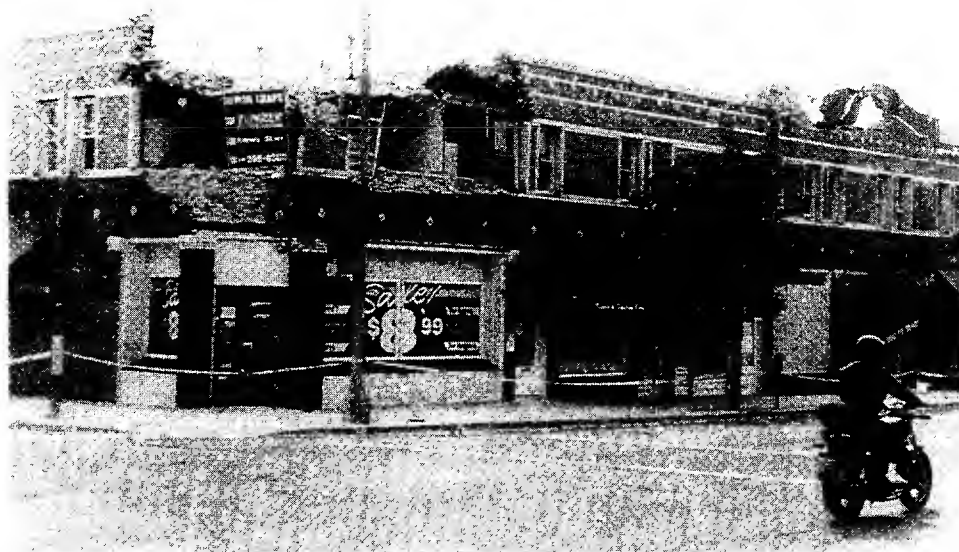
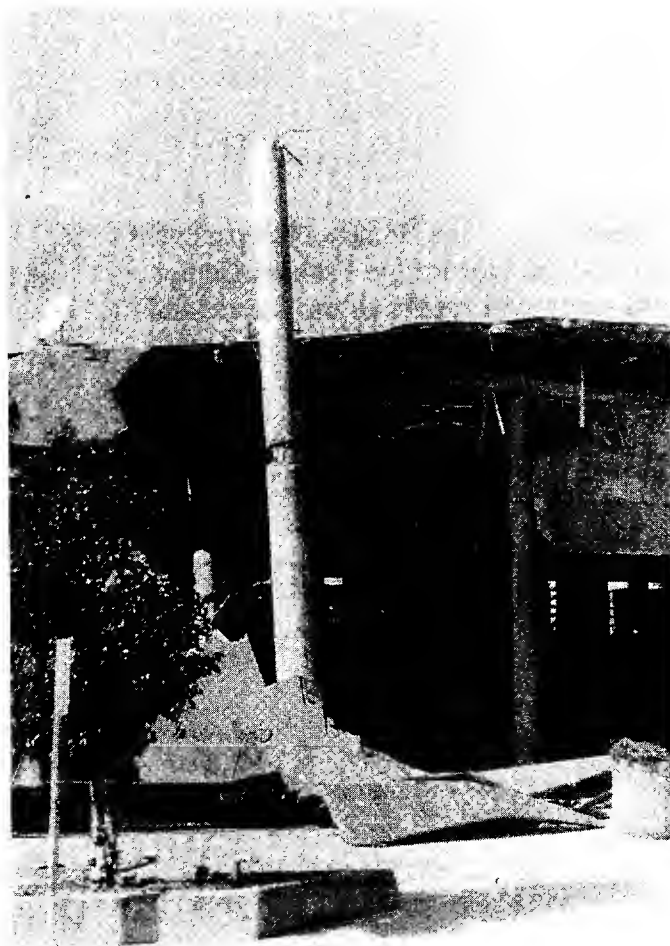


Figure 12 Damage to unreinforced masonry buildings, even those that had been rehabilitated, was common. Upper stories and corners were particularly vulnerable to damage. The rows of light-colored diamonds on the face of this building are the end plates of through-bolts used to connect the wall to the floor joists, a typical rehabilitation technique. The remains of parapet braces can be seen on the roof.



Figure 13 The corner of this rehabilitated unreinforced masonry apartment building in East Hollywood crumbled on all four stories.

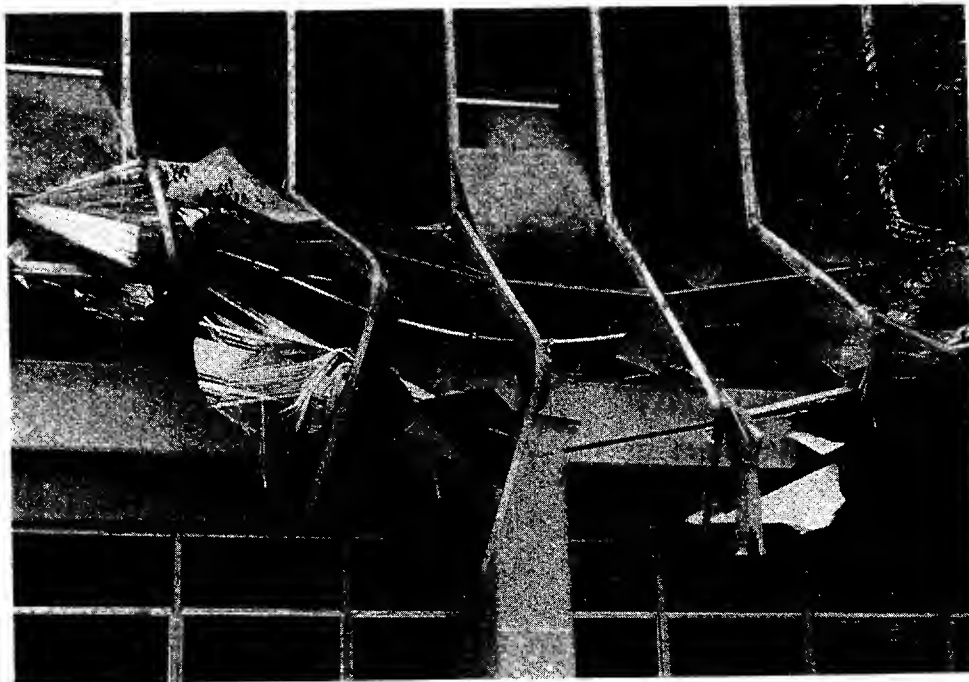


Figure 14 The second story of the concrete frame Kaiser Permanente office building on Balboa Avenue in Northridge completely collapsed. The first story was relatively undamaged, suggesting it was far stiffer than the story above.

Figure 15 The exposed concrete frame of the Kaiser Permanente building, revealing deep beams, suggests that the building had a strong-beam, weak-column configuration. Except for the second story columns, the columns and beams remained intact while the joints disintegrated.



Figure 16 The stiff infill panels of the Barrington Building effectively shortened the concrete columns, forcing all the displacement into the column sections bounded by windows. Diagonal X-cracking decreased in severity towards the top of the building.

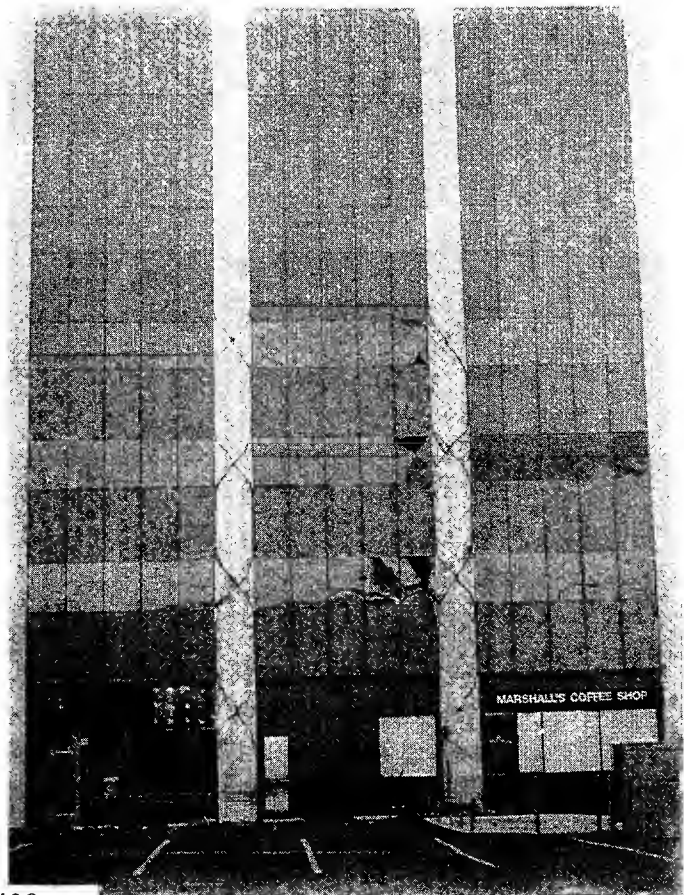


Figure 17 The first-story columns of the steel-framed building housing the American Savings Bank on Topanga Canyon Road in Canoga Park flexed during the quake and ended up slightly displaced from their original positions.

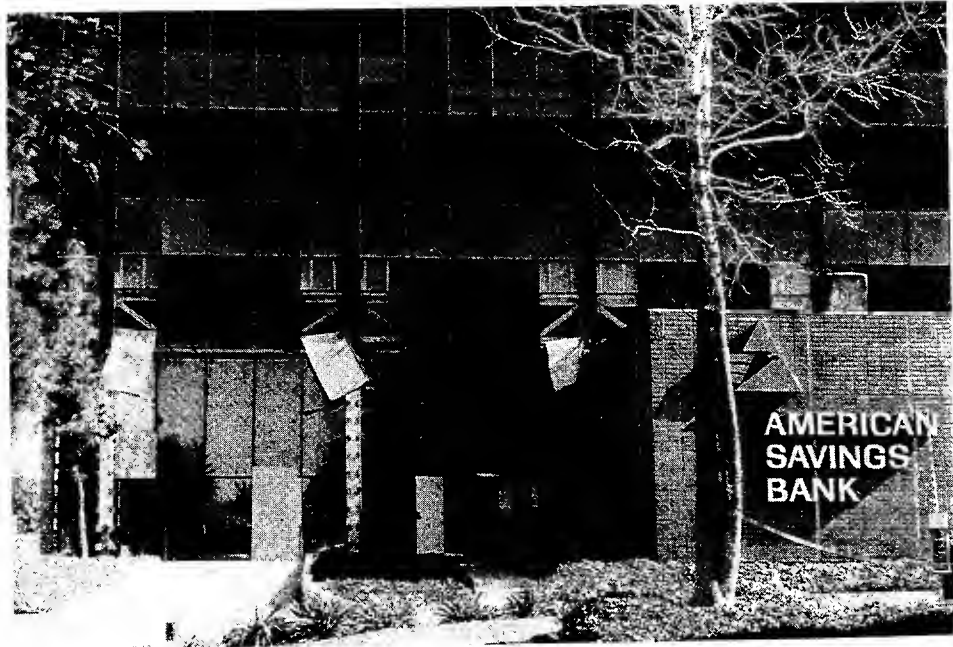
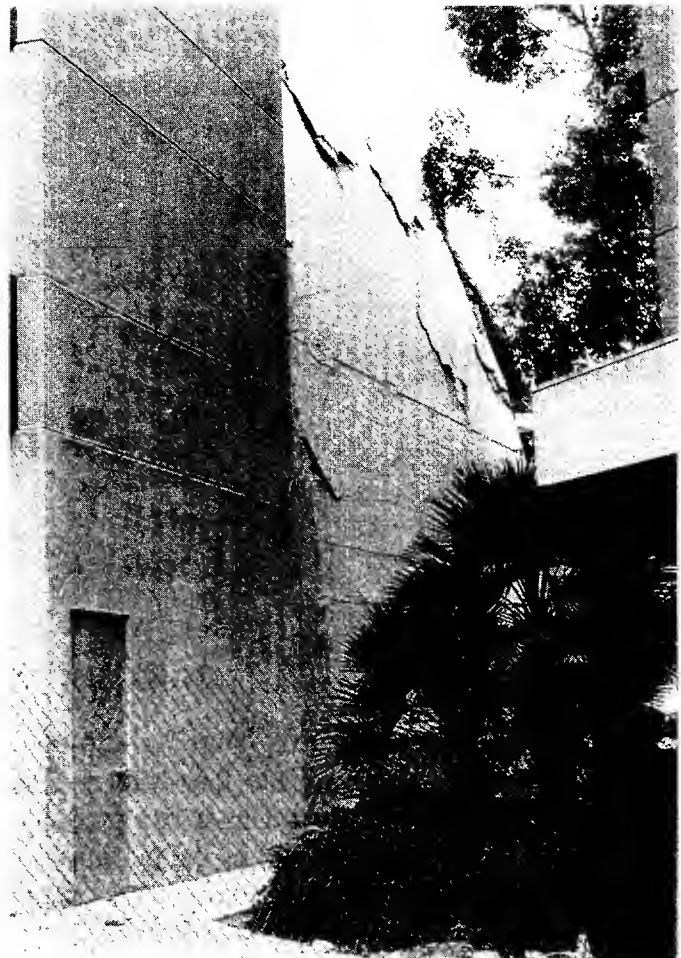


Figure 18 The three-year old four-level parking garage at the Northridge campus of California State University partially collapsed in the earthquake. The collapse apparently started at the interior, causing the exterior walls to be pulled in to the middle of the structure. Precast concrete "trees" were connected to form a moment-resisting frame at the exterior of the structure.



Figure 19 The cast-in-place concrete parking garage at the Kaiser Permanente Hospital complex in West Los Angeles collapsed in on itself. The moment frame that provided lateral resistance on the south face of the structure could not resist the out-of-plane forces apparently caused by the collapse of interior elements.

Figure 20 - At the east and west faces of the Kaiser Permanente Hospital parking garage, shear walls made up the lateral force resisting system. Both walls had horizontal cracks caused by the out-of-plane bending when the walls were pulled inward. Neither wall had major diagonal cracking, suggesting that the lateral load was never fully delivered to the walls. The stair towers remained erect. The east wall and stair tower are shown here.



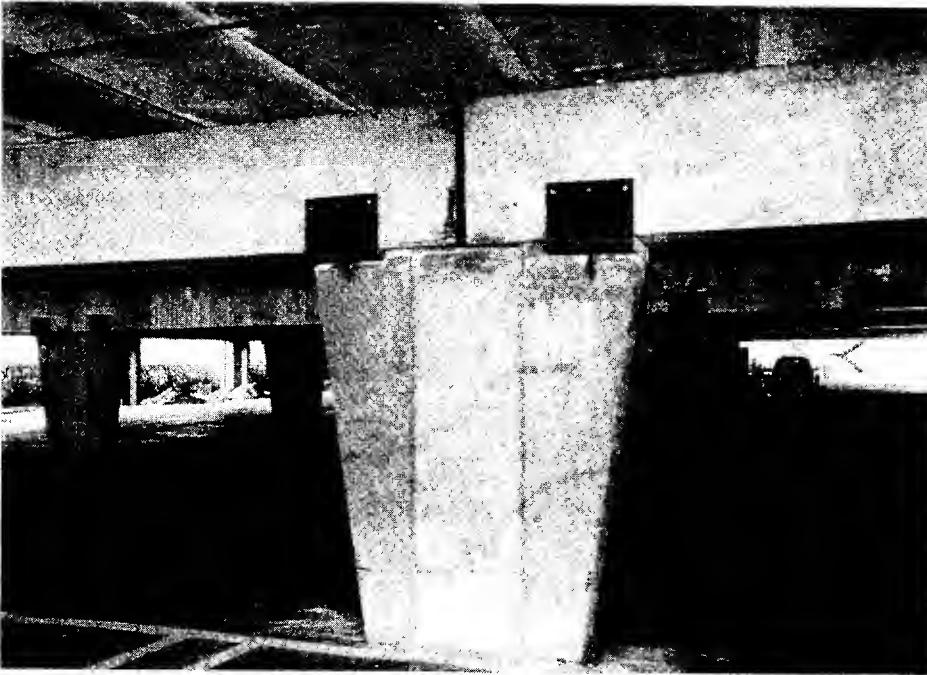


Figure 21 The interior columns of the two-level parking garage at the Trans World Bank in Sherman Oaks had been seismically strengthened after it suffered damage in the 1971 San Fernando quake. The interior columns fared well in the 1994 Northridge quake.



Figure 22 The exterior columns of the Trans World Bank parking garage, which had not been strengthened, were badly damaged.

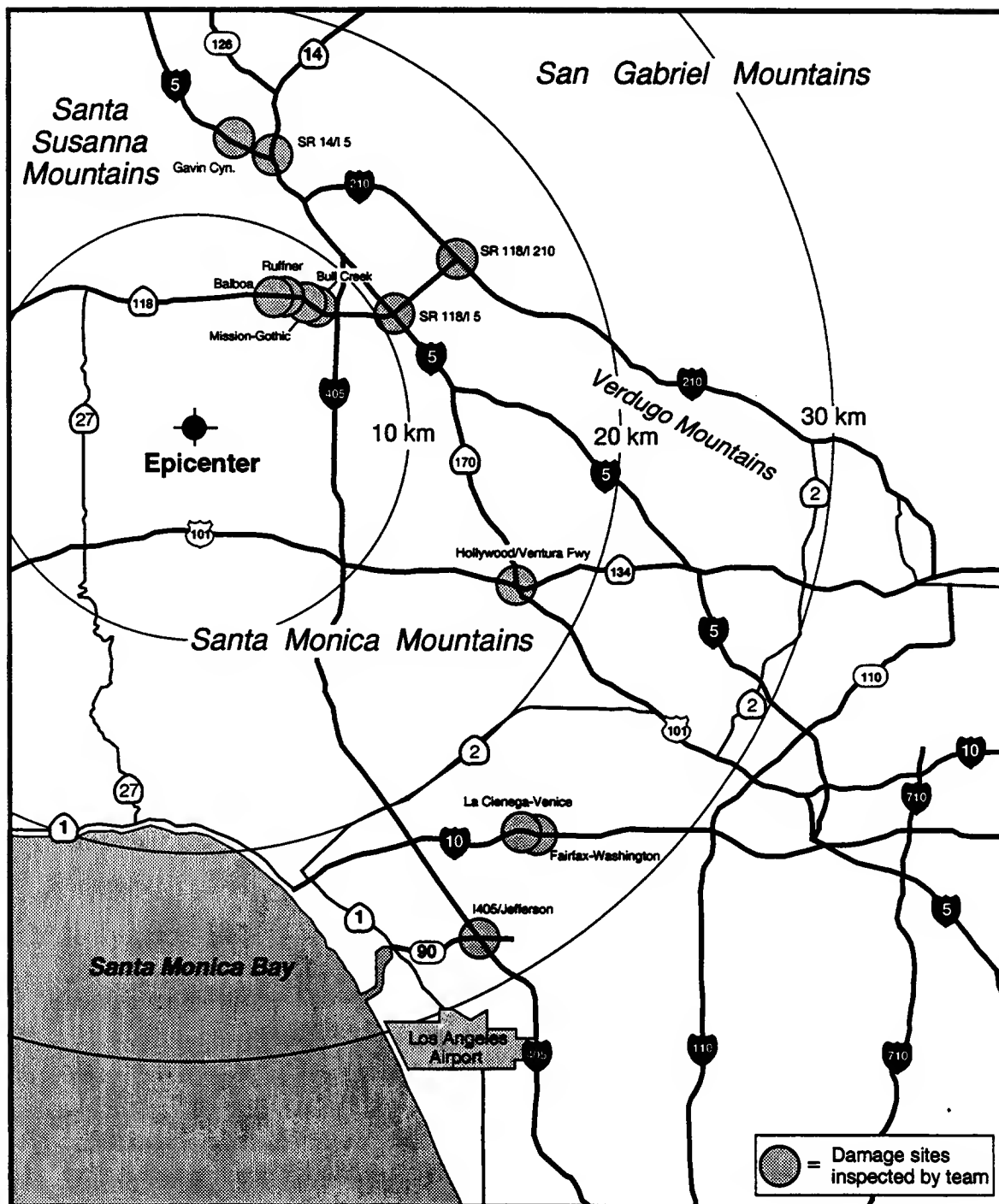


Figure 23 Bridge damage sites studied by the reconnaissance team



Figure 24 Aerial view of the bridge at Gavin Canyon, looking to the east, showing appearance of the four end spans shortly after demolition had begun



Figure 25 Ground level view of the southbound bridge at Gavin Canyon, looking to the northwest, showing the hinge bearing seat near Bent 3.

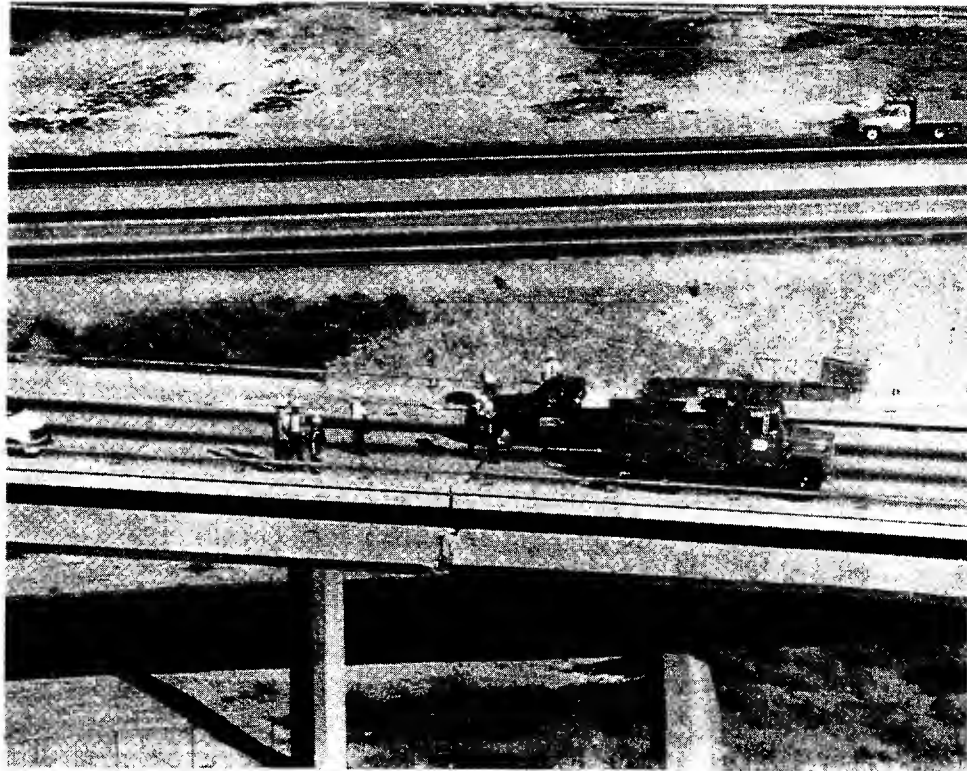


Figure 26 Example of pounding and offset at a hinge in the SR14/I5 interchange

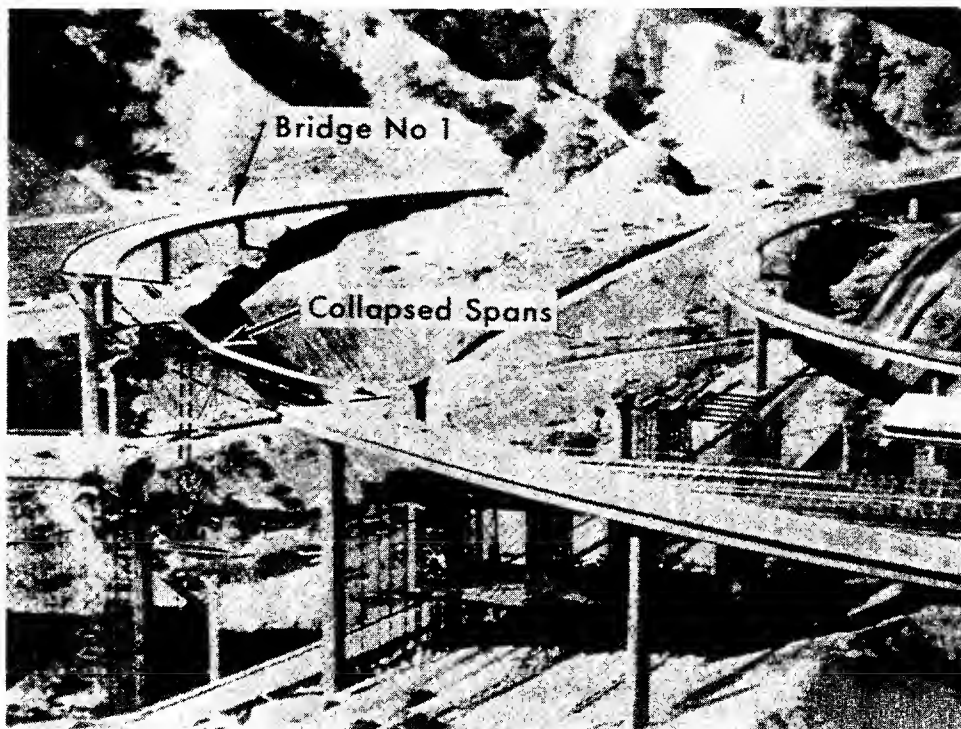


Figure 27 SR14/I5 interchange after the 1971 San Fernando earthquake. View looking to the west, showing collapsed South Connector Overcrossing



Figure 28 Overview of the collapse of the SR14/I5 Separation and Overhead, Ramp C, looking to the south at Abutment 1. Pier 3 can be seen at the right of the photograph (Courtesy of EERC)



Figure 29 Damage at Pier 3 of the SR14/I5 Separation and Overhead, Ramp C, looking to the west (Courtesy of EERC)



Figure 30 Collapsed portion of the SR14/I5 North Connector Overcrossing, looking east.. Pier 2 was at the left, near the broken hinge on the ground (Courtesy of EERC)

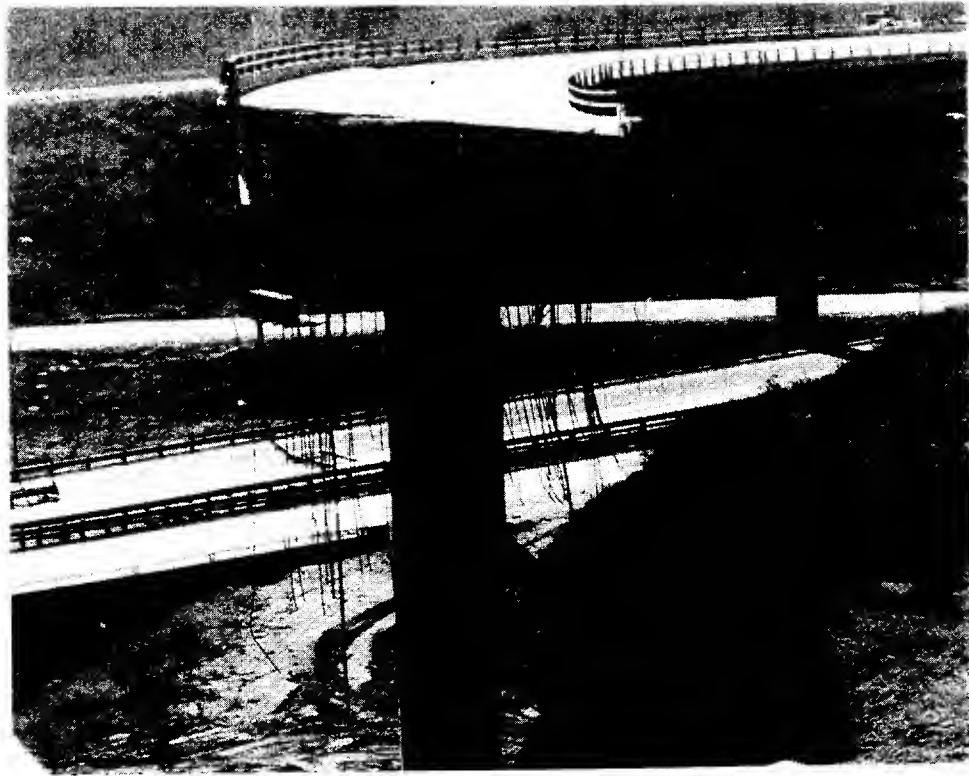


Figure 31 View of the flexural failure at Pier 3 of the SR14/15 North Connector Overcrossing, looking to the south



Figure 32 View of crushed Pier 2 and the hinge near Pier 2 (Courtesy EERC)

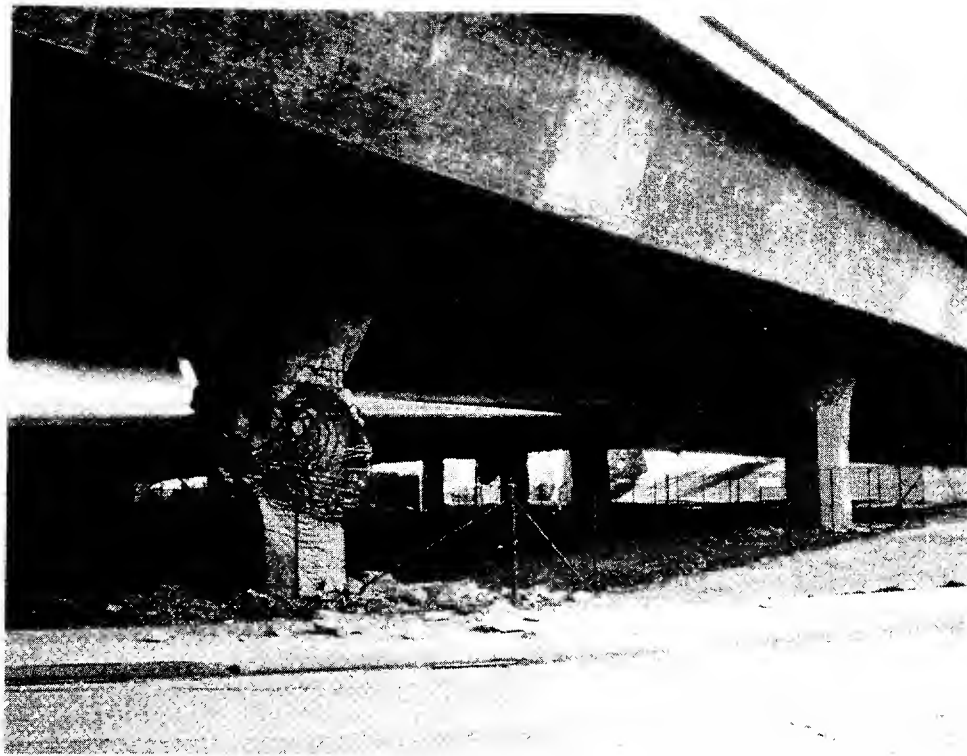


Figure 33 Damage to piers of the SR118 Mission-Gothic Undercrossing, looking to the northwest at the north face of the westbound bridge, Bents 3 (foreground) and 2.



Figure 34 Damage to a pier of the SR118 Mission-Gothic Undercrossing, looking to the northwest at the southernmost pier of Bent 3 of the westbound bridge.



Figure 35 Damage to pier 3S-1 of State Route 118 at Bull Creek Canyon Channel, looking to the northwest



Figure 36 Damage to piers of Bent 3S of State Route 118 at Bull Creek Canyon Channel, looking to the southeast.



Figure 37 Collapsed westbound lane of I10 at Venice Blvd.; pier of Bent 7 in foreground

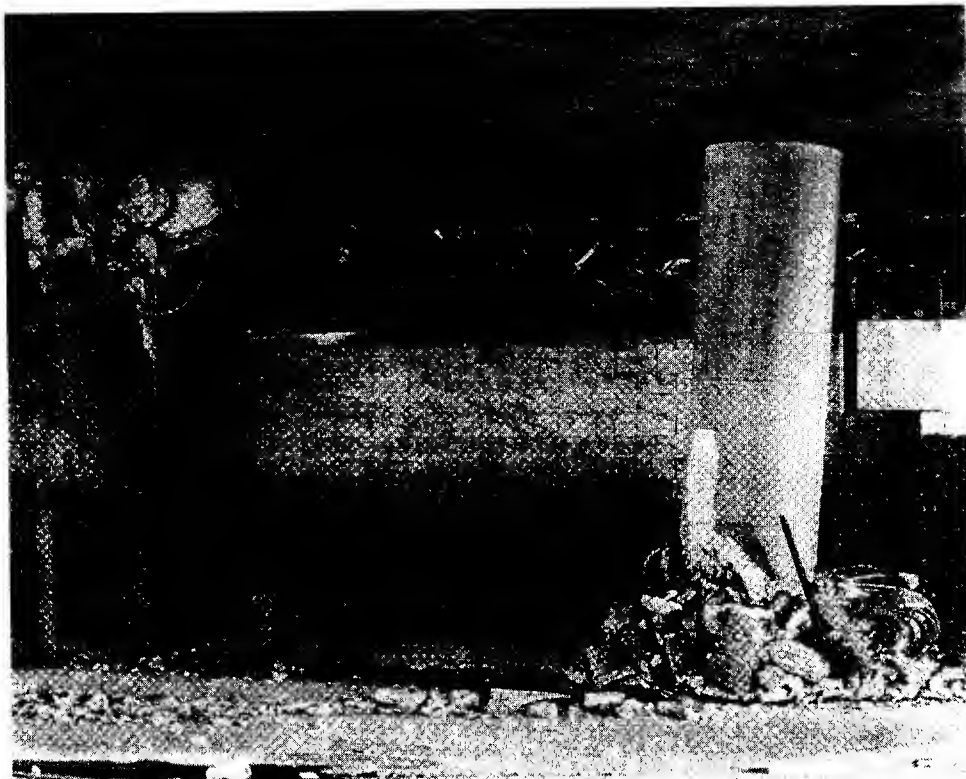


Figure 38 Failed piers in Bent 7 supporting westbound lane of I10 at Venice Blvd.



Figure 39 Northernmost pier of Bent 6 supporting westbound lane of I10 (west of Venice Blvd.)



Figure 40 Piers of Bent 3 supporting eastbound lane of I10 at La Cienega Blvd.

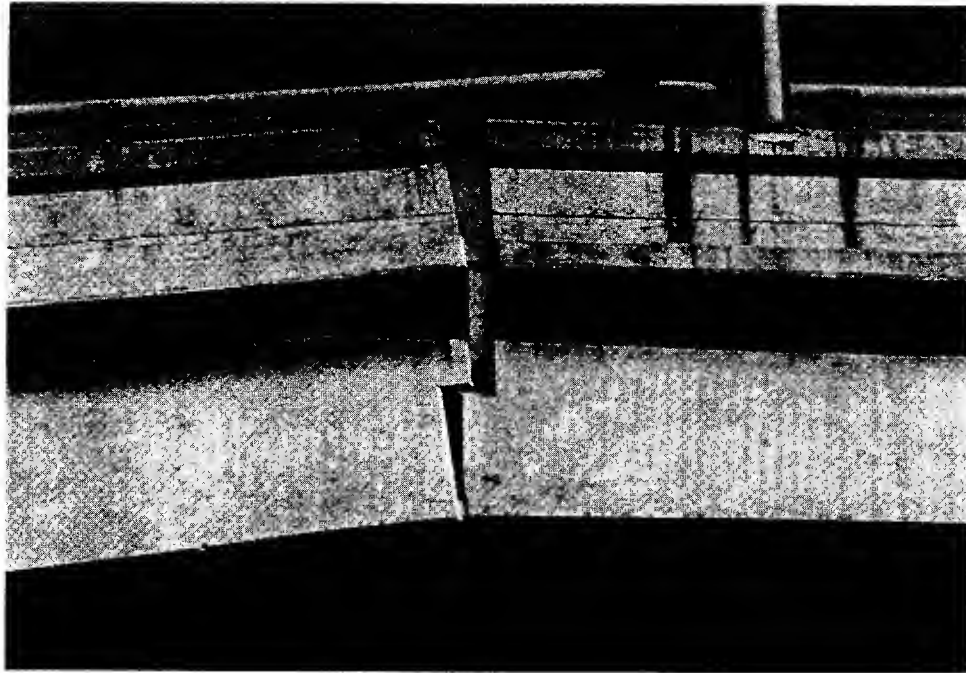


Figure 41 Hinge adjacent to Bent 4 of I 10 at Fairfax Ave.; cable restrainers prevented loss of support (Courtesy of EERC)

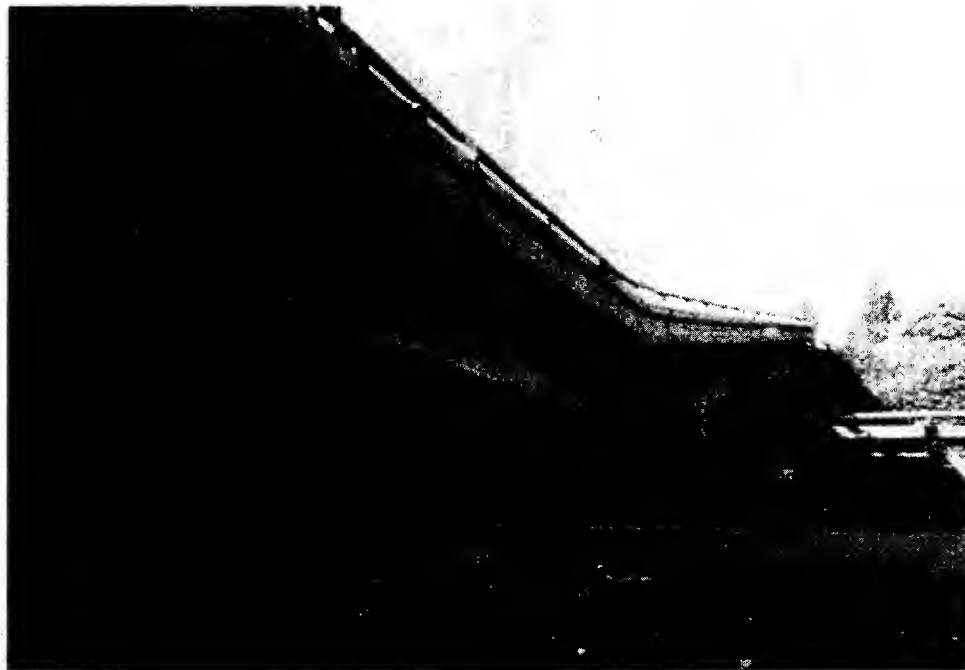


Figure 42 View of collapsed span of I10 over Fairfax Ave.; note rotation of girder over Pier 2 (Courtesy of EERC)



Figure 43 Failed column in Bent 3 of I10 at Fairfax Ave. (Courtesy of EERC)



Figure 44 The steel pipeline at Terminal Hill separated from its supporting saddle at several places and pipe sections bulged at other locations along the alignment.

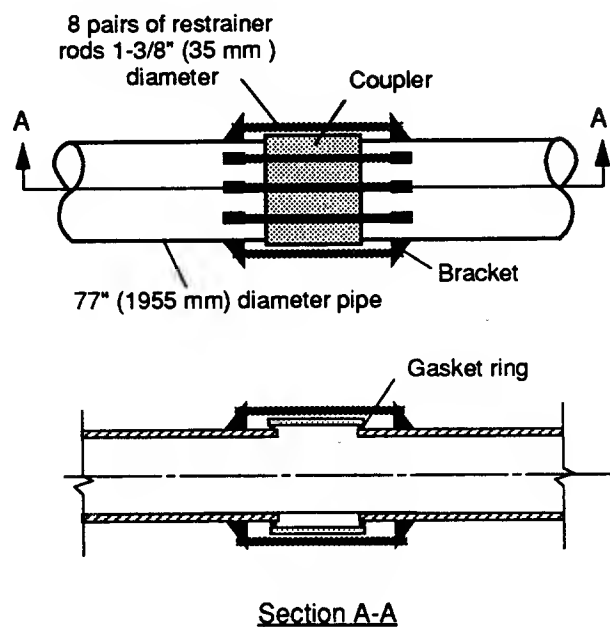


Figure 45 Schematic drawing of connection of the two steel pipe sections which were pulled apart during the earthquake.

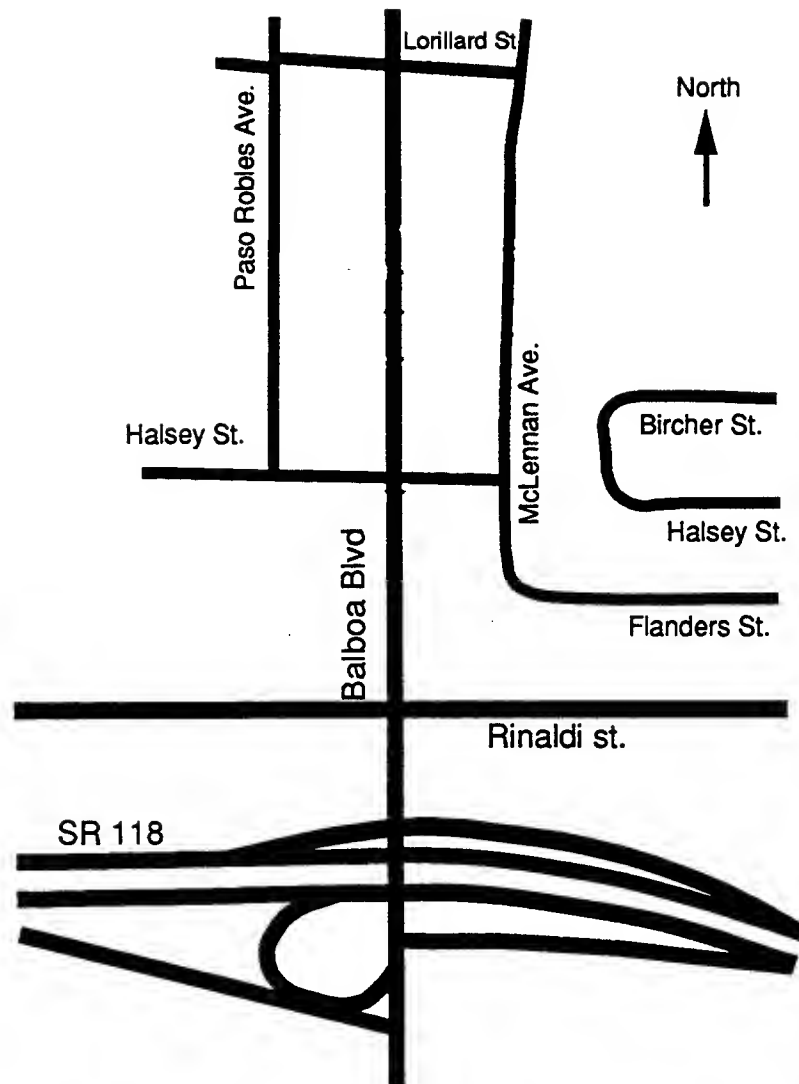


Figure 46 Location of the 0.6-m gas main rupture on Balboa Boulevard.



Figure 47 Ground contraction along Balboa Boulevard caused the rupture of a gas distribution line, the Rinaldi trunk water main, and a gas main.

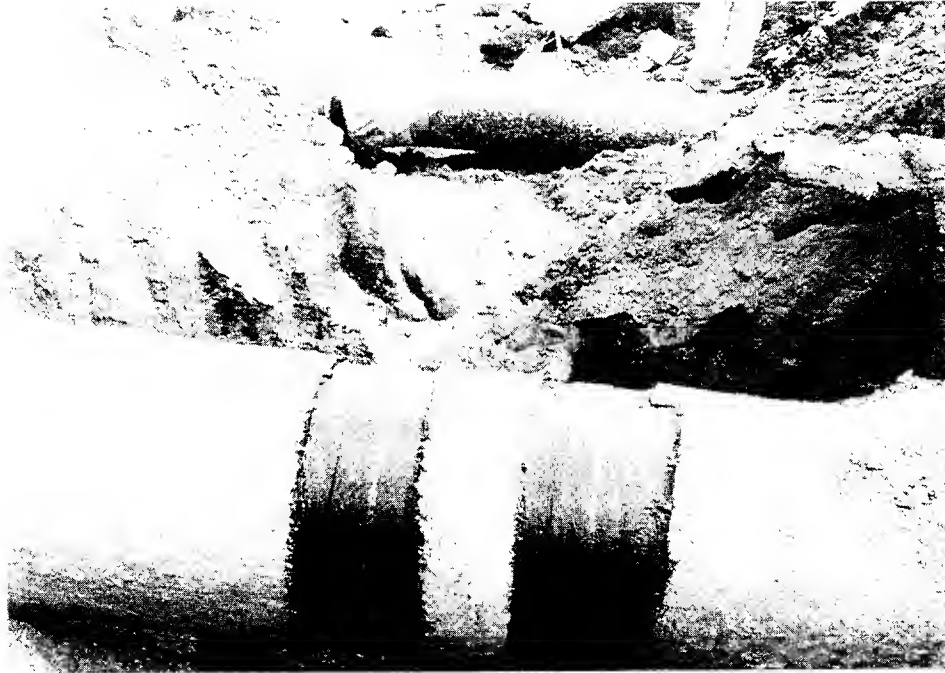


Figure 48 Ground extension along Balboa Boulevard resulted in the rupture of the same gas main and water main shown in Figure 47. The rupture of the gas main here caused a major fire that engulfed five houses.



Figure 49 Houses destroyed by a fire resulting from the rupture of the 0.6-m gas main along Balboa Boulevard.

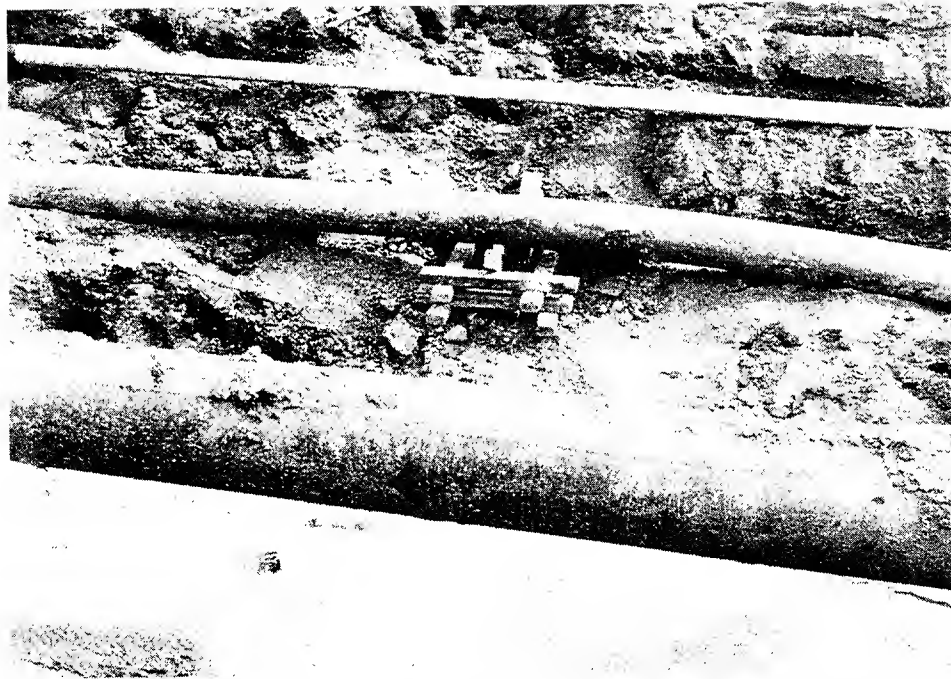


Figure 50 Some of the buried pipelines located near the intersection of Balboa Boulevard and Bircher Street--the potential hazard of co-location of lifeline systems. At this site are three water lines (two of them main lines); three gas lines; two sewers; one crude oil line; overhead power, telephone, and cable TV lines; the street lighting system; and the street itself.

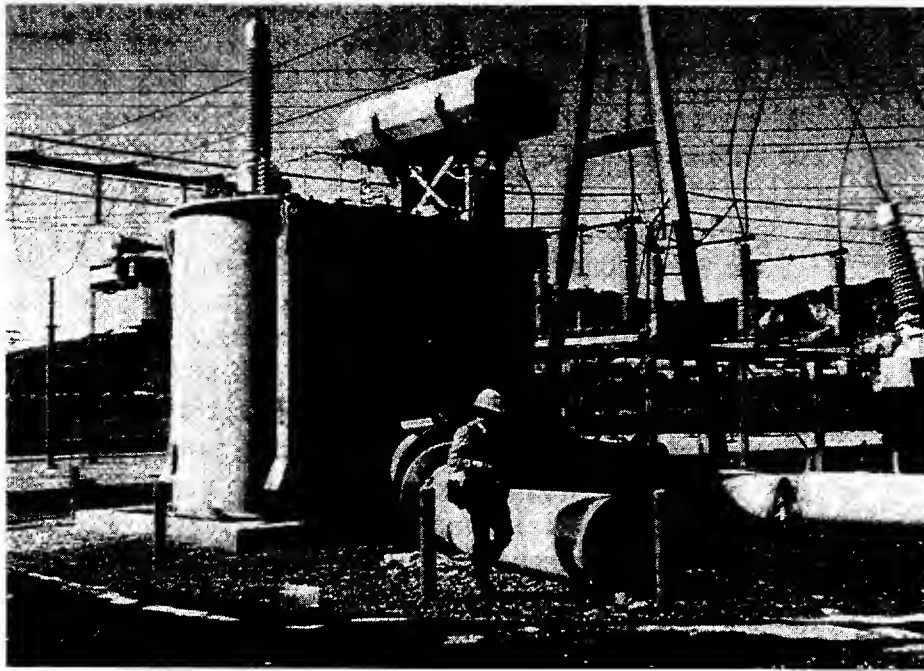
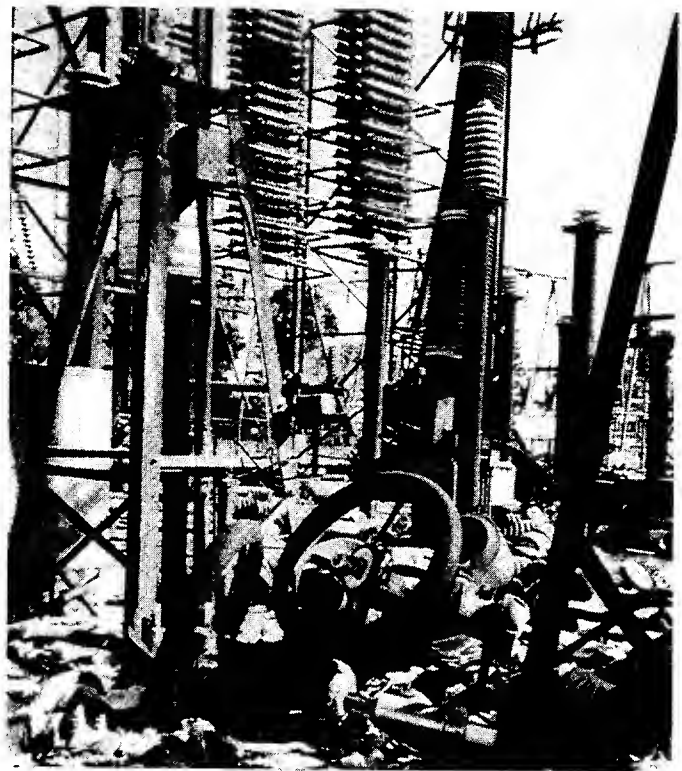


Figure S1 Damage to DC equipment at several high voltage substations, such as this one at Sylmar, led to widespread power outages in the Los Angeles area as well as isolated outages throughout seven western states. (Photo courtesy of Edward Matsuda, Pacific Gas and Electric Company.)

Figure S2 Porcelain is an integral part of high voltage electrical equipment due to insulation requirements and is also the most vulnerable to damage during strong earthquake shaking. (Photo courtesy of Edward Matsuda, Pacific Gas and Electric Company.)



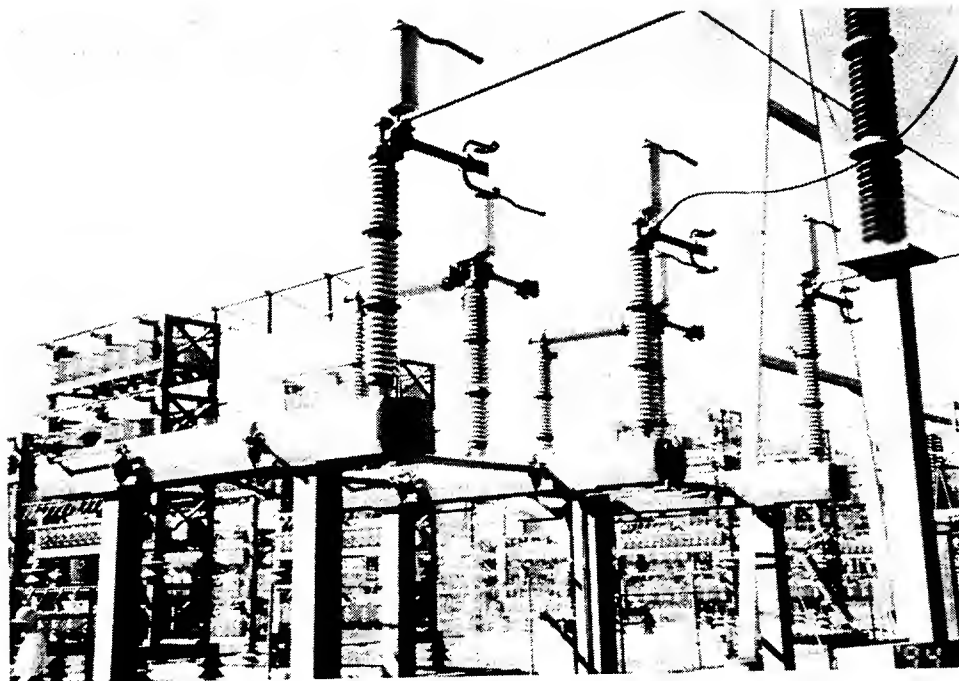


Figure 53 Most of the 230 kV circuit switchers (in the forefront) at the Sylmar substation were damaged. Most of the capacitor banks (in the background) performed well in this earthquake, whereas most collapsed during the 1971 quake. (Photo courtesy to Edward Matsuda of Pacific Gas and Electric Company.)

Figure 54 Derailment of a 64-car freight train in Northridge. The incident resulted in the spill of 30,000 liters of sulfuric acid and 7,500 liters of diesel fuel.

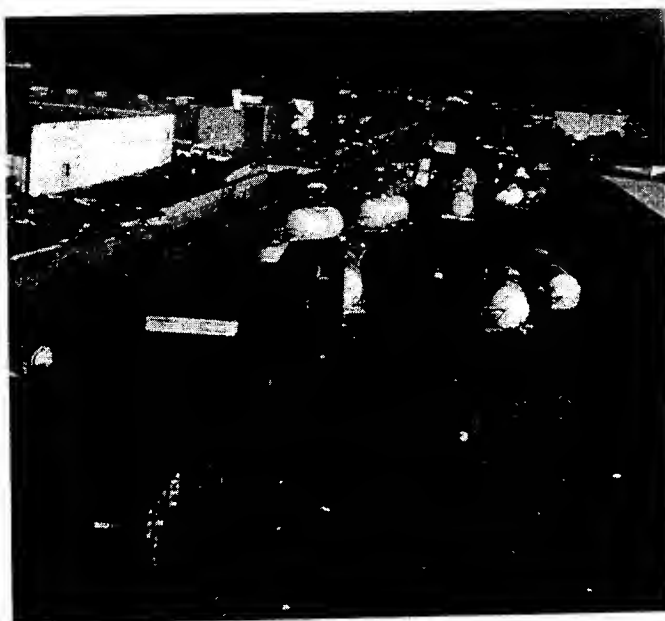


Figure 55
Transverse cracks
in pavement along
Balboa Boulevard
in Northridge area.



Figure 56 Fire damage in a single story commercial building.



Figure 57 Fire damage in a two story commercial building.



Figure 58 Fire damage in a three story commercial building.



Figure 59 Partially collapsed apartment building with fire damage in the rear.

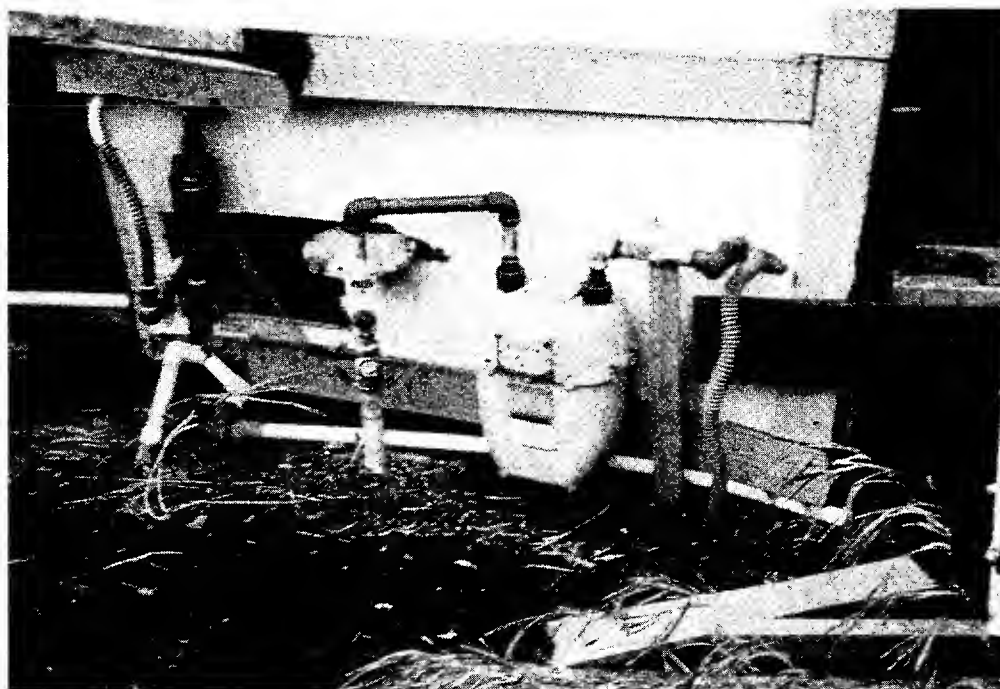


Figure 60 Damaged gas service in a manufactured housing development.



Figure 61 Multi-family residential building destroyed by fire.



Figure 62 University science building damaged by fire.